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ABSTRACT

This educational guide concerns exploring the moon. Activities are divided into three units: Pre-Apollo, Learning from Apollo, and The Future. These correspond, at least roughly, to exercises that can be done before the Lunar Sample Disk (available from NASA) arrives to the school (Pre-Apollo), while it is there (Learning from Apollo), and after it has been returned to NASA (The Future). Activities include: (1) "Moon ABCs Fact Sheet"; (2) "Rock ABCs Fact Sheet"; (3) "Progress in Lunar Science Chart"; (4) "Nearside of the Moon--Apollo Landing Sites"; (5) "Distance to the Moon"; (6) "Diameter of the Moon"; (7) "Reaping Rocks"; (8) "The Lunar Disk"; (9) "Apollo Landing Sites"; (10) "Regolith Formation"; (11) "Lunar Surface"; (12) "Differentiation"; (13) "Impact Craters"; (14) "Clay Lava Flows"; (15) "Lava Layering"; (16) "Lunar Landing Sites"; (17) "Lunar Roving Vehicle"; (18) "Moon Anomalies"; (L9) "Lunar Land Use"; (20) "Life Support Systems"; and (21) "Lunar Biospheres". (MVL)

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EXPLORING THE MOON

a Teacher's Guide with activities for Earth and Space Sciences

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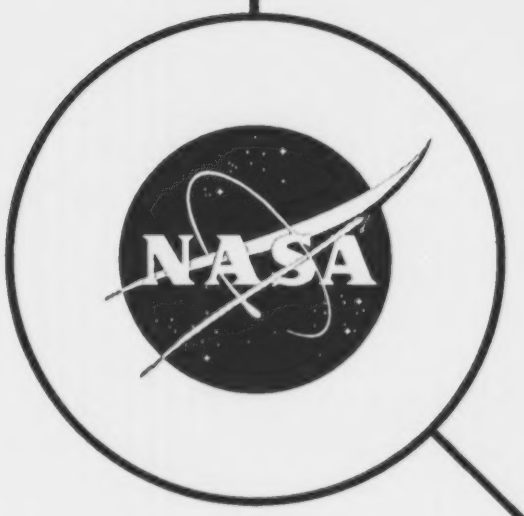
EXPLORING THE MOON

a Teacher's Guide with activities for Earth and Space Sciences



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Office of Human Resources and Education
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About the cover
Our knowledge and concepts of the Moon change over time as depicted by the three images.
A map of the Moon (circa 1700s) is overlaid by an Apollo 11 astronaut footprint (NASA photo AS11-40-5878) and a NASA painting of a future lunar habitation module by Pat Rawlings of Science Applications International Corporation.

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About this Book

These materials have been designed for use in upper elementary through high schools especially, but not exclusively, with the Lunar Sample Disk. See Page iv.

This book contains:

- information on the Lunar Sample Disk,
- Activity Matrices -- Skills & Standards,
- a Teacher's Guide,
- Moon ABCs Fact Sheet,
- Rock ABCs Fact Sheet,
- Progress in Lunar Science Chart,
- 17 activities,
- Resource Section for each unit,
- Glossary,
- NASA Educational Resources.

The "Teacher's Guide" titled "The Moon: Gateway to the Solar System," pages 1-16, provides background information about the Moon. It tells the story of the Moon's geological history and how scientists try to decipher the story. This background information may be useful reading for students as well. Key facts about the Moon appear on the "Moon ABCs" and "Rock ABCs" pages. These pages were named to emphasize the basic nature of the information. The "Progress in Lunar Science Chart" summarizes our knowledge about the Moon from 1959 to 1997.

The activities are divided into three units: Pre-Apollo, Learning from Apollo, and the Future. These correspond, at least roughly, to exercises that can be done before the Lunar Sample Disk arrives at your school (Pre-Apollo), while it is there (Learning from Apollo), and after it has been returned to NASA (The Future).

The length of time needed to complete an activity will vary according to the degree of difficulty and the development level of the students. Thus activities may take one to eight or more class periods.

"Activity Matrices" are provided to assist in identifying the science process skills and science and mathematics educational standards associated with each activity.

Classroom activities promote problem-solving, communication skills, and teamwork. Each activity consists of teacher pages and reproducible student sheets.

Teacher pages begin with a statement of purpose and background information with answers specific to the activity. Relevant pages in the "Teacher's Guide" also are listed. These are followed by sections on preparation, in-class suggestions, wrap-up ideas, and extensions. Words that are bolded appear in the Glossary.

Student sheets include a purpose statement, key words, list of materials, procedure, questions with space provided for answers, and charts. Key words are included in the Glossary. Materials for each activity are listed in order of use. They are bolded in the text of the procedure section as a memory aid for students.

A note on measurements: These activities use metric units of measure with the few exceptions when English units are used to describe items from the material lists such as pans or measuring cups.

About the Lunar Sample Disk

Legacy of Apollo

The collection of rocks and regolith from the Moon is a tangible legacy of the U.S. Apollo Space Program. NASA makes a small portion of this "extraterrestrial" material available for classroom use through the Lunar Sample Loan Program.

Lunar Sample Loan Program

Six samples of rocks and regolith are embedded in a 15-cm diameter plastic disk. Disks are sent via registered mail to educators for one- to two-week loan periods. The package also includes this book *Exploring the Moon*, an annotated slide set of lunar images (described more fully on Page v), and a collection of color photographs and descriptions of the six samples.

How to Schedule a Disk

Educators must first be certified to borrow lunar material by attending a training seminar on security requirements and proper handling procedures. This is the same certification as for borrowing the Meteorite Sample Disk. Then a written request must be sent to a NASA Educator Resource Center at least one month prior to the requested loan date. Contact the NASA Educator Resource Center that serves your geographic area for more information on certification seminars and request procedures (refer to Page 146 of this book for addresses and phone numbers.)

Ninth grade science students from Waipahu High School, Hawai'i view the Lunar Sample Disk as part of an activity from *Exploring the Moon*.

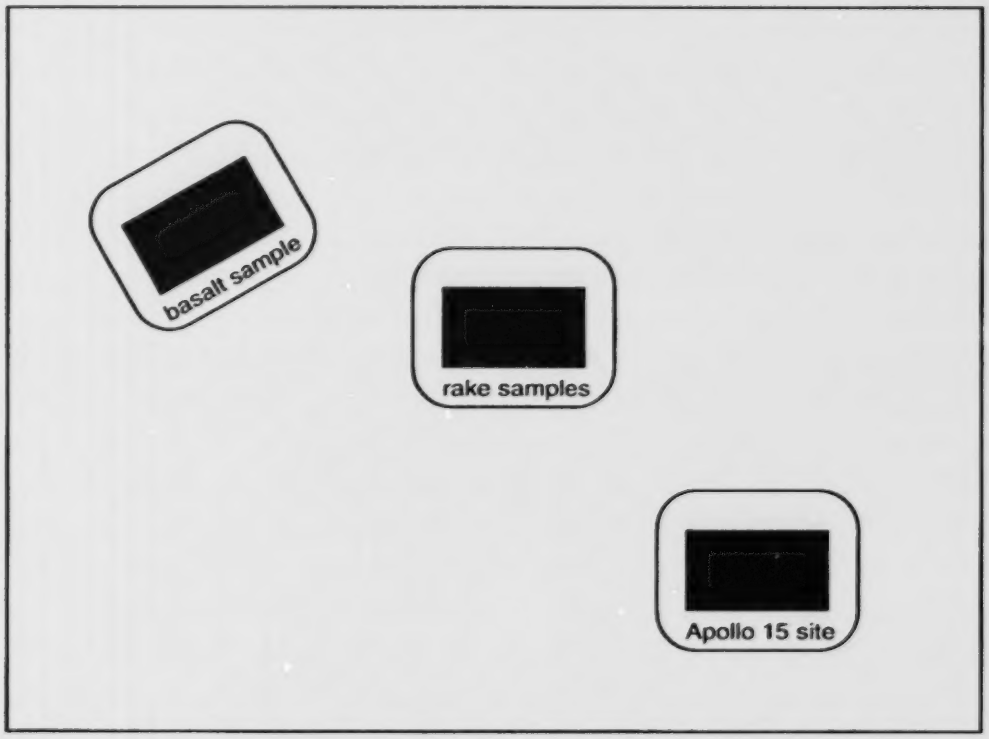
About the Slide Set

The Collection

A set of thirty-six 35-mm slides has been assembled to complement the activities in this book *Exploring the Moon.* Each slide is accompanied by detailed captions. Topics include what we knew about the Moon from telescopic and other astronomic observations before Apollo, Apollo missions, astronaut activities on the lunar surface, the Highlands, the Maria, how the Moon formed, and exciting ideas for future explorations.

How to Obtain a Copy

It is easy to obtain a copy of the slides. They are available from the Central Operation of Resources for Educators (CORE) in Ohio or from NASA Educator Resource Centers. Phone calls are welcome if you are unable to visit the Educator Resource Center that serves your geographic area. Please refer to Page 146 in this book for addresses and phone numbers for CORE and Educator Resource Centers.



Activity Matrix

Science Process Skills

		Observing	Classifying	Communicating	Physical Modeling	Measuring	Collecting & Organizing Data	Inferring	Predicting	Formulating Hypotheses	Interpreting Data	Controlling Variables	Decision Making	Debating
Unit 1 Pre-Apollo	Distance to the Moon	○		○		○	○				○			
	Diameter of the Moon	○		○		○	○				○			
	Reaping Rocks	○	○	○		○	○		○		○		○	
Unit 2 Learning From Apollo	The Lunar Disk	○	○	○		○	○		○		○		○	
	Apollo Landing Sites	○	○	○			○				○			
	Regolith Formation	○		○	○		○	○	○	○	○	○	○	
	Lunar Surface	○	○	○	○		○	○						
	Differentiation	○	○	○	○		○		○		○			
	Impact Craters	○		○	○	○	○	○	○	○	○	○	○	
	Clay Lava Flows	○		○	○	○	○	○			○	○	○	
	Lava Layering	○		○	○		○	○			○		○	
	Lunar Landing Sites	○	○	○	○		○	○			○		○	○
	Lunar Roving Vehicle	○		○	○		○				○	○	○	
	Moon Anomalies			○			○	○		○	○		○	○
Unit 3 Future	Lunar Land Use		○	○	○		○	○	○	○	○		○	○
	Life Support Systems	○	○	○	○	○	○	○	○	○	○	○	○	○
	Lunar Biosphere	○	○	○	○	○	○	○	○	○	○	○	○	○

Activity Matrix

Science Standards

		Unifying Concepts & Processes	Science as Inquiry	Physical Science	-properties of objects & materials	-position, motions and forces of objects	-interactions of energy & matter	Earth & Space Science	-properties of earth materials	-objects in the sky	Life Science	-characteristics of organisms	-organisms & environment	-populations & ecosystems	-interdependence of organisms	Science & Technology	Science in Personal & Social Perspectives
Unit 1 Pre-Apollo	Distance to the Moon	○	○	○		○		○		○							
	Diameter of the Moon	○	○					○		○							
	Reaping Rocks	○	○	○	○		○	○	○	○							
Unit 2 Learning From Apollo	The Lunar Disk	○	○	○	○		○	○	○	○							
	Apollo Landing Sites	○	○	○	○		○	○	○	○							
	Regolith Formation	○	○	○	○	○	○	○	○	○							
	Lunar Surface	○	○	○	○	○	○	○	○	○							
	Differentiation	○	○	○	○	○	○	○	○	○							
	Impact Craters	○	○	○	○	○	○	○	○	○							
	Clay Lava Flows	○	○	○	○	○	○	○	○	○							
	Lava Layering	○	○	○	○	○	○	○	○	○							
	Lunar Landing Sites	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
	Lunar Roving Vehicle	○	○	○	○	○	○	○	○	○	○	○	○			○	
	Moon Anomalies	○	○	○	○	○	○	○	○	○							
Unit 3 Future	Lunar Land Use	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
	Life Support Systems	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
	Lunar Biosphere	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

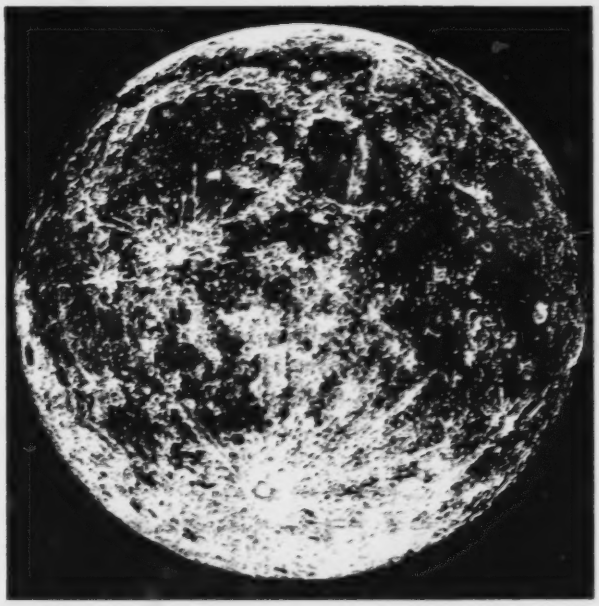
Activity Matrix

Mathematics Standards

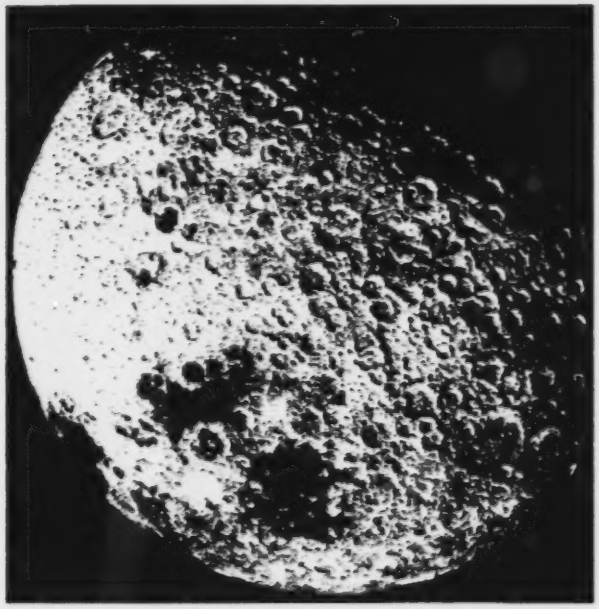
		Problem Solving	Measurement	Number & Number Relationships	Computation & Estimation	Geometry
Unit 1 Pre-Apollo	Distance to the Moon	○		○	○	
	Diameter of the Moon	○	○	○	○	○
	Reaping Rocks		○			
Unit 2 Learning From Apollo	The Lunar Disk		○			
	Apollo Landing Sites					○
	Regolith Formation					
	Lunar Surface					○
	Differentiation	○				
	Impact Craters	○	○	○	○	○
	Clay Lava Flows	○	○	○	○	○
	Lava Layering					○
	Lunar Landing Sites	○		○	○	
	Lunar Roving Vehicle	○		○	○	
	Moon Anomalies					
Unit 3 Future	Lunar Land Use			○	○	
	Life Support Systems	○	○	○	○	○
	Lunar Biosphere	○	○	○	○	○

THE MOON
GATEWAY TO THE SOLAR SYSTEM

G. Jeffrey Taylor, PhD



WHEN ASTRONAUTS dug into the Moon's surface during the Apollo program, they were doing more than digging up dry, dark sediment. They were time travelers. The rocks and sediment returned by Apollo contain vital clues to how Earth and the Moon formed, the nature and timing of early melting, the intensity of impact bombardment and its variation with time, and even the history of the Sun. Most of this information, crucial parts of the story of planet Earth, cannot be learned by studying rocks on Earth because our planet is so geologically active that it has erased much of the record. The clues have been lost in billions of years of mountain building, volcanism, weathering, and erosion. Colliding tectonic plates



The Moon, front and back

The **top right** photograph is a telescopic image of the Earth-facing half of the Moon obtained at Lick Observatory in California. The one **below right** was taken during the Apollo 16 mission and shows mostly the farside, except for the dark areas on the left, which can be seen, though barely, from Earth. The two major types of terrain are clearly visible. The *highlands*, which are especially well displayed in the photograph of the farside, are light-colored and heavily cratered. The *maria* are darker and smoother; they formed when lava flows filled depressions. One of the mysteries about the Moon is why fewer maria occur on the farside than nearside. Note how many craters stand shoulder to shoulder on the farside. These immense holes chronicle the Moon's early bombardment, an intense barrage that probably affected the early Earth as well.

and falling rain have erased much of Earth history, especially the early years before four billion years ago.

The Moon was geologically active in its heyday, producing a fascinating array of products, but its geologic engine was not vigorous and all records of early events were not lost. Its secrets are recorded in its craters, plains, and rocks. This guide reveals the secrets that lunar scientists have uncovered since the Apollo missions returned 382 kilograms (843 pounds) of rock and sediment from the lovely body that graces the night sky.

The emphasis here is on geology. The samples returned by Apollo are the stars of the show. [See the "Lunar Disk" activity on Pages 39–42 and the "Apollo Landing Sites" activity on Pages 43–46.] Understanding the Moon, however, requires other geological approaches, such as geological mapping from high-quality photographs, the study of analogous features on Earth (for instance, impact craters), and experiments in laboratories.

THE LUNAR LANDSCAPE

The Moon is not like Earth. It does not have oceans, lakes, rivers, or streams. It does not have wind-blown ice fields at its poles. Roses and morning glories do not sprout from its charcoal gray, dusty surface. Redwoods do not tower above its cratered ground. Dinosaur foot prints cannot be found. Paramecium never conjugated, amoeba never split, and dogs never barked. The wind never blew. People never lived there—but they have wondered about it for centuries, and a few lucky ones have even visited it.

Highlands and lowlands

The major features of the Moon's surface can be seen by just looking up at it. It has lighter and darker areas. These distinctive terrains are the bright lunar highlands (also known as the lunar terrae, which is Latin for "land") and the darker plains called the lunar maria, Latin for "seas," which they resembled to Thomas Hariot and Galileo Galilei, the first scientists to examine the Moon with telescopes. The names terrae and maria were given to lunar terrains by Hariot and Galileo's contemporary, Johannes Kepler. In fact, the idea that the highlands and maria correspond to lands and seas appears to have been popular among ancient Greeks long before telescopes were invented. Although we now know they are not seas (the Moon never had any water), we still use the term maria, and its singular form, mare.

The highlands and craters

Closer inspection shows that the highlands comprise countless overlapping craters, ranging in size from the smallest visible in photographs (1 meter on the best Apollo photographs) to more than 1000 km. Essentially all of these craters formed when meteorites crashed into the Moon. Before either robotic or piloted spacecraft went to the Moon, many scientists thought that most lunar craters were volcanic in origin. But as we found out more about the nature of lunar craters and studied impact craters on Earth, it became clear that the Moon has been bombarded by cosmic projectiles. The samples returned by the Apollo missions confirmed the pervasive role impact processes play in shaping the lunar landscape.

The term "meteorite impact" is used to describe the process of surface bombardment by cosmic object. The objects themselves are variously referred to as "impactors" or "projectiles."

The impact process is explosive. A large impactor does not simply bore its way into a planet's surface. When it hits, it is moving extremely fast, more than 20 km/sec (70,000 km/hour). This meeting is not tender. High-pressure waves are sent back into the impactor and into the target planet. The impactor is so overwhelmed by the passage of the shock wave that almost all of it vaporizes, never to be seen again. The target material is compressed strongly, then decompressed. A little is vaporized, some melted, but most (a mass of about 10,000 times the mass of the impactor) is tossed out of the target area, piling up around the hole so produced. The bottom of the crater is lower than the original ground surface, the piled up material on the rim is higher. This is the characteristic shape of an impact crater and is different from volcanic calderas (no piled up materials) or cinder cones (the central pit is above the original ground surface). A small amount of the target is also tossed great distances along arcuate paths called rays.

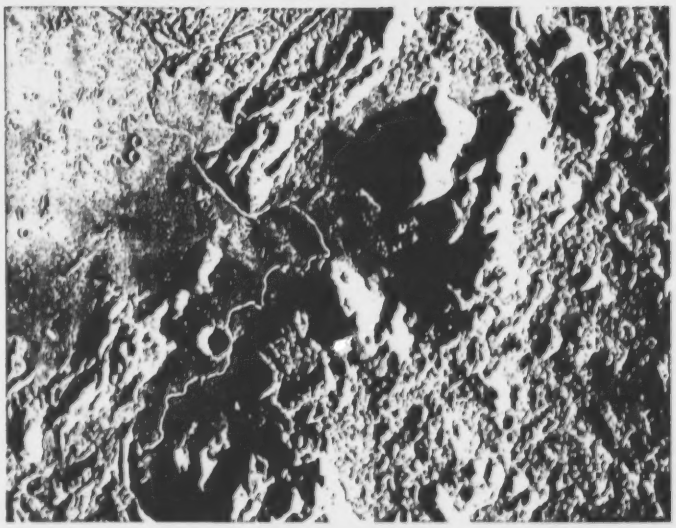
Real impacts cannot be readily simulated in a classroom. In fact, there are very few facilities where we can simulate high-velocity impacts. Nevertheless, classroom experiments using marbles, ball bearings, or other objects can still illustrate many important

points about the impact process. For example, objects impacting at a variety of velocities (hence kinetic energies) produce craters with a variety of sizes; the more energy, the larger the crater. [See the "Impact Craters" activity on Pages 61–70.]

The maria

The maria cover 16% of the lunar surface and are composed of lava flows that filled relatively low places, mostly inside immense impact basins. So, although the Moon does not have many volcanic craters, it did experience volcanic activity. Close examination of the relationships between the highlands and the maria shows that this activity took place after the highlands formed and after most of the cratering took place. Thus, the maria are younger than the highlands. [See the "Clay Lava Flows" activity on Pages 71–76 and the "Lava Layering" activity on Pages 77–82.]

How do we know that the dark plains are covered with lava flows? Why not some other kind of rock? Even before the Apollo missions brought back samples from the maria, there were strong suspicions that the plains were volcanic. They contain some features that look very much like lava flows. Other features resemble lava channels, which form in some types of lava flows on Earth. Still other features resemble collapses along underground volcanic features called lava tubes. These and other features convinced most lunar scientists before the Apollo missions that the maria were lava plains. This insight was confirmed by samples collected from the maria: they are a type of volcanic rock called basalt.



Rivers or lava channels?

The origin of river-like valleys, called rilles, was debated before the Apollo 15 mission visited one of them, Hadley Rille, shown here from orbit (white arrow shows the landing site) and from the lunar surface. Some scientists argued that rilles were river valleys, implying that the Moon had flowing water at one time. Others thought that rilles resembled the channels that form in lava flows. Observations by the Apollo 15 crew and samples returned settled the argument: rilles are volcanic features.

The maria fill many of the gigantic impact basins that decorate the Moon's nearside. (The Moon keeps the same hemisphere towards Earth because Earth's gravity has locked in the Moon's rotation.) Some scientists contended during the 1960s that this demonstrated a cause and effect: impact caused not only the formation of a large crater but led to melting of the lunar interior as well. Thus, it was argued, the impacts triggered the volcanism. However, careful geologic mapping using high-quality telescopic images, showed that the mare must be considerably younger than the basins in which they reside. For example, the impact that formed the large Imbrium basin (the Man-in-the-Moon's right eye) hurled material outwards and sculpted the mountains surrounding the Serenitatis basin (the left eye); thus, Serenitatis must be older. The Serenitatis basin is also home to Mare Serenitatis. If the lavas in Mare Serentatis formed when the basin did, they ought to show the effects of the giant impact that formed Imbrium. They show no

Lava flows dribbling across Mare Imbrium

Long lava flows (lower left to upper right through center of photo) in Mare Imbrium. The flows are up to 400 kilometers long (the entire extent is not shown in this Apollo photograph) and have 30-meter high cliffs at their margins. The ridges running roughly perpendicular to the flows are called wrinkle ridges. The ridges formed after the flows because they did not impede the advance of the lava flow. The smooth plains surrounding the prominent lava flows are also lava, but older, so the margins are harder to see. The craters on the right along the ridge are about 5 kilometers in diameter.

signs of it. Furthermore, the maria contain far fewer craters than do basin deposits, hence have been around a shorter time (the older the surface, the greater the number of craters). The Apollo samples, of course, confirmed these astute geological observations and showed that the maria filling some basins formed a billion years after the basin formed.

One other type of deposit associated with the maria, though it blankets highlands areas as well, is known as dark mantle deposits. They cannot be seen except with telescopes or from spacecraft near the Moon, but are important nonetheless. Before Apollo, most scientists believed that the dark mantle deposits were formed by explosive volcanic eruptions known as pyroclastic eruptions (literally, "pieces of fire"). Some deposits seemed to be associated with low, broad, dark cinder cones, consistent with the idea that they were formed by pyroclastic eruptions—this is how cinder cones form on Earth. This bit of geologic deduction was proven by the Apollo 17 mission and its sampling of the "orange soil," a collection of tiny glass droplets like those found in terrestrial pyroclastic eruptions.

Maria mysteries

Some mysteries persist about the maria. For one, why are volcanoes missing except for the cinder cones associated with dark mantle deposits? Second, if no obvious volcanoes exist, where did the lavas erupt from? In some cases, we can see that lava emerged from the margins of enormous impact basins, perhaps along cracks concentric to the basin. But in most cases, we cannot see the places where the lava erupted. Another curious feature is that almost all the maria occur on the Earth-facing side of the Moon. Most scientists guess that this asymmetry is caused by the highlands crust being thicker on the lunar farside, making it difficult for basalts to make it all the way through to the surface. [See the "Moon Anomalies" activity on Pages 91–98.]

THE DUSTY LUNAR SURFACE

Some visitors to Kilauea Volcano, Hawai'i, have been overheard to say, upon seeing a vast landscape covered with fresh lava, "It looks just like the Moon." Well, it doesn't. The fresh lava flows of Kilauea and other active volcanoes are usually dark grayish and barren like the Moon, but the resemblance ends there. The lunar surface is charcoal gray and sandy, with a sizable supply of fine sediment. Meteorite impacts over billions of years have ground up the formerly fresh surfaces into powder. Because the Moon has virtually no atmosphere, even the tiniest meteorite strikes a defenseless surface at its full cosmic velocity, at least 20 km/sec. Some rocks lie strewn about the surface, resembling boulders sticking up through fresh snow on the slopes of Aspen or Vail. Even these boulders won't last long, maybe a few hundred million years, before they are ground up into powder by the relentless rain of high-speed projectiles. Of course, an occasional larger impactor arrives, say the size of a car, and excavates fresh rock from beneath the blanket of powdery sediment. The meteoritic rain then begins to grind the fresh boulders down, slowly but inevitably.

The powdery blanket that covers the Moon is called the lunar regolith, a term for mechanically produced debris layers on planetary surfaces. Many scientists also call it the "lunar soil," but it contains none of the organic matter that occurs in soils on Earth. Some people use the term "sediment" for

regolith. Be forewarned that the regolith samples in the Lunar Sample Disk are labeled "soil." Although it is everywhere, the regolith is thin, ranging from about two meters on the youngest maria to perhaps 20 meters in the oldest surfaces in the highlands. [See the "Regolith Formation" activity on Pages 47–52.]

Lunar regolith is a mixed blessing. On the one hand, it has mixed local material so that a shovelful contains most of the rock types that occur in an area. It even contains some rock fragments tossed in by impacts in remote regions. Thus, the regolith is a great rock collection. It also contains the record of impacts during the past several hundred million to a billion years, crucial information for understanding the rate of impact on Earth during that time. On the other hand, this impact record is not written very clearly and we have not come close to figuring it out as yet. The blanket of regolith also greatly obscures the details of the bedrock geology. This made field work during Apollo difficult and hinders our understanding of lunar history.

The regolith consists of what you'd expect from an impact-generated pile of debris. It contains rock and mineral fragments derived from the original bedrock. It also contains glassy particles formed by the impacts. In many lunar regoliths, half of the particles are composed of mineral fragments that are bound together by impact glass; scientists call these objects agglutinates. The chemical composition of the regolith reflects the composition of the bedrock underneath. Regolith in the highlands is rich in aluminum, as are highland rocks. Regolith in the maria is rich in iron and magnesium, major constituents of basalt. A little bit of mixing from beneath basalt layers or from distant highland locales occurs, but not enough to obscure the basic difference between the highlands and the maria.

Raking moon dirt

One of the most useful ways of obtaining samples of Moon rocks was to drag a rake through the regolith. This allowed rock fragments larger than about one centimeter to remain on tines of the rake, while smaller fragments fell through. Note the large range in the sizes of rock fragments. One large boulder lies near the rake, a medium-sized one is visible between the astronaut's feet, along with countless other pebbles. Most of the regolith is smaller than fine sand. The astronaut's footprints are distinct because the regolith is composed of a large percentage of tiny particles (about 20% is smaller than 0.02 millimeters).

A geologist-astronaut does field work on the Moon

Geologist Harrison H. Schmitt examines a large rock at the Apollo 17 landing site. This large boulder contains numerous rock fragments that were smashed together by the huge impact event that made the 750-kilometer Serentatis basin on the Moon.

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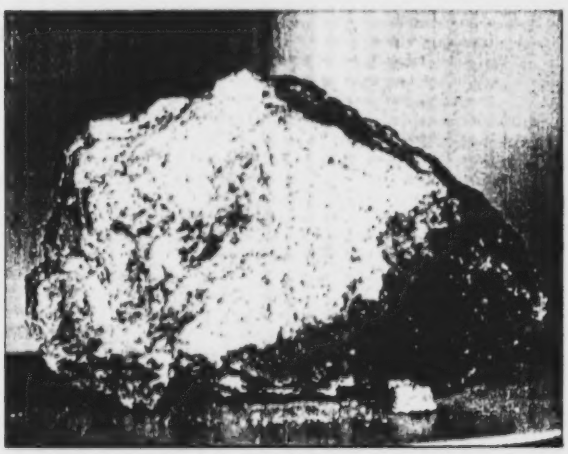
One of the great potential bits of information stored in the complex pile atop the lunar surface is the history of the Sun. The nearest star puts out prodigious amounts of particles called the solar wind. Composed mostly of hydrogen, helium, neon, carbon, and nitrogen, the solar wind particles strike the lunar surface and are implanted into mineral grains. The amounts build up with time. In principle, we can determine if conditions inside the Sun have changed over time by analyzing these solar wind products, especially the isotopic composition of them.

The same solar wind gases may prove useful when people establish permanent settlements on the Moon. Life support systems require the life-giving elements: hydrogen and oxygen (for water), carbon, and nitrogen. Plenty of oxygen is bound in the silicate, minerals of lunar rocks (about 50% by volume) and the solar wind provided the rest. So, when the astronauts were digging up lunar regolith for return to Earth, they were not merely sampling—they were prospecting!

MOON ROCKS

Geologists learn an amazing amount about a planet by examining photographs and using other types of remotely sensed data, but eventually they need to collect some samples. For example, although geologists determined unambigously from photographs that the maria are younger than the highlands, they did not know their absolute age, the age in years. Rocks also provide key tests to hypotheses. For instance, the maria were thought to be covered with lava flows, but we did not know for sure until we collected samples from them. Also, no method can accurately determine the chemical and mineralogical composition of a rock except laboratory analysis. Most important, samples provide surprises, telling us things we never expected. The highlands provide the best example of a geological surprise, and one with great consequences for our understanding of what Earth was like 4.5 billion years ago.



A fist-sized piece of the original lunar crust

This rock sample was collected during the Apollo 15 mission. It is an anorthosite, a rock composed of little else but the mineral feldspar. Anorthosites formed from the enormous magma system, the *lunar magma ocean*, that surrounded the newly formed Moon. Because of its importance in understanding the origin of the Moon's crust, the rock was nicknamed the "genesis rock."

Smash and mix, mix and melt

This rock returned by the Apollo 16 mission attests to the effects of impacts on a planet's crust. It is a hodgepodge of rock and mineral fragments, some of which themselves are complicated mishmashes of rock debris. Geologists call these complicated rocks *breccias*.

Highland rocks, the lunar magma ocean, and maybe a cataclysm

Strange as it may seem, the first highland rocks were collected during the first lunar landing, the Apollo 11 mission, which landed on a mare, Mare Tranquillitatis. Although most of the rocks collected were, indeed, basalts, some millimeter-sized rock fragments were quite different. They were composed chiefly of the mineral plagioclase feldspar; some fragments were composed of nothing but plagioclase. [See the "Rock ABCs Fact Sheet" on Page 19.] Such rocks are called anorthosites. Some scientists suggested that these fragments were blasted to the Apollo 11 landing site by distant impacts on highland terrain. Thus, they argued, the highlands are loaded with plagioclase. This was a bold extrapolation confirmed by subsequent Apollo missions to highland sites.

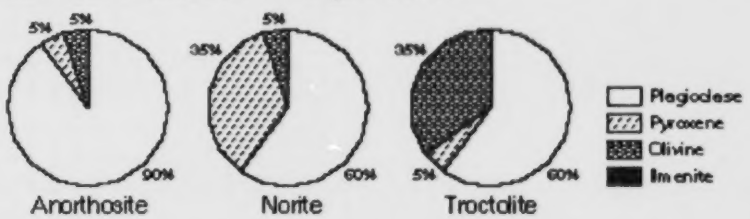
But this was not enough for some scientists. If the highlands are enriched in plagioclase, how did they get that way? One way is to accumulate it by flotation in a magma (molten rock). This happens in thick subterranean magma bodies on Earth. So, plagioclase floated in a magma. But if ALL the lunar highlands are enriched in plagioclase, then the magma must have been all over the Moon. The early Moon must have been covered by a global ocean of magma, now commonly referred to as the lunar magma ocean. Although some scientists still remain unconvinced about the veracity of the magma ocean hypothesis, nothing we have learned since has contradicted the idea that 4.5 billion years ago the Moon was covered by a layer of magma hundreds of kilometers thick. The idea has been extended to the young Earth as well, and even to Mars and some asteroids. And all this sprung forth because creative and bold scientists saw special importance in a few dozen white fragments of anorthosite strewn about in a pile of charcoal gray lunar regolith.

The magma ocean concept was tested by the 1994 U. S. Clementine Mission to the Moon. Clementine was in a pole-to-pole orbit for two months, during which it took thousands of photographs in several wavelengths. Scientists at the University of Hawai'i developed a method to determine the iron content of the lunar surface from ratioes of the intensity of light reflected in different wavelengths. The magma ocean hypothesis predicts that the lunar highlands should have low iron contents, less than about 5 wt. % (when recorded as iron oxide, FeO). According to Clementine measurements, the highlands average slightly under 5 wt. % FeO, consistent with the magma ocean idea. Further refinement of this test is underway using data from Clementine and the forthcoming U. S. Lunar Prospector Mission, scheduled for launch in early 1998.

The highlands also contain other types of igneous rocks. The most abundant are called norites and troctolites, rocks composed of equal amounts of plagioclase and either olivine or pyroxene (both silicate minerals containing iron and magnesium). Age dating suggests that these rocks are slightly younger than the anorthosites and formed after the magma ocean had crystallized.

Highland rocks are difficult to work with because all that cratering, so evident in photographs of the highlands, has taken its toll on the rocks. Most highland rocks are complex mixtures of other rocks. The original igneous rocks have been melted, mixed, smashed, and generally abused by impacts during the Moon's first half billion years. We call these complicated rocks breccias. Some are so mixed up that they contain breccias within breccias within breccias. Most of the anorthosites, norites, and troctolites are actually rock fragments inside breccias. Separating them out is painstaking work.

Mineral abundances in highland rocks



An interesting thing about highland breccias, especially those we call impact melt breccias (rocks partly melted by an impact event), is that most of them fall into a relatively narrow span of ages, from about 3.85 to 4.0 billion years. This has led some scientists to propose (boldly again--lunar scientists don't seem to be timid!) that the Moon was

bombarded with exceptional intensity during that narrow time interval. If it happened, it probably affected Earth as well, perhaps leading to production of the first sedimentary basins, and possibly inhibiting the formation of the first life on this planet or harming whatever life had developed by four billion years ago. This idea of a cataclysmic bombardment of the Moon is not yet proven. It could be that the apparent clustering in rock ages reflects poor sampling—we may only have obtained samples from one or two large impact basins. The idea can be tested by obtaining samples from many more localities on the Moon.

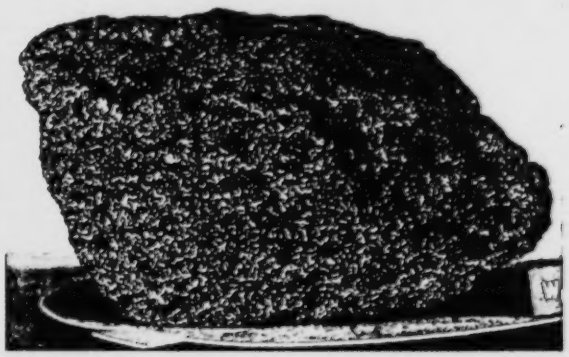
Multi-ringed masterpieces

The Moon has about 35 multi-ringed, circular impact features larger than 300 km in diameter. The one shown here, the Orientale basin, has three very prominent rings. The diameter of the outer one is 930 km. These immense craters might all have formed in a narrow time interval between 3.85 and 4.0 billion years ago. Scientists do not know for sure how the rings form during the impact.

Many highland breccias and a few igneous rocks are enriched compared to other lunar samples in a set of elements not familiar to most of us. The elements are those that tend not to enter the abundant minerals in rocks. The result is that as a magma crystallizes the part that is still liquid becomes progressively richer in these special elements. The rocks that contain them are called KREEP, for potassium (chemical symbol K), rare-earth elements (abbreviated REE), and phosphorus (P). Most Moon specialists believe that KREEP represents the last dregs from the crystallization of the magma ocean. Huge impacts dug down to the lower crust of the Moon and excavated it, mixing it with other debris to form KREEPy breccias.

The maria: lava flows and fountains of fire

The missions to mare areas brought back lots of samples of basalt. Basalts differ from the highlands rocks in having more olivine and pyroxene, and less

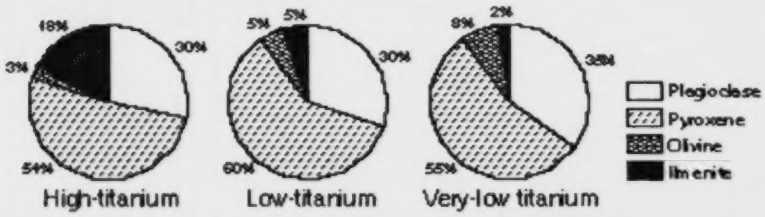


A piece of a lava flow

This typical sample of a mare basalt is composed mostly of brown pyroxene (grayish in the photo) and white feldspar. The holes in the sample are frozen gas bubbles. Some basalt samples have many such bubbles (called vesicles by geologists), whereas others have none.

plagioclase. Many of them also have surprisingly large amounts of an iron-titanium oxide mineral called ilmenite. The first batch had so much ilmenite (and some other related minerals) that they were called "high-titanium" mare basalts, in honor of the exceptional titanium contents compared to terrestrial basalts. The second mission, Apollo 12, returned basalts with lower titanium concentrations, so they were called "low-titanium" mare basalts. Subsequent missions, including an automated sample-return mission sent by the Soviet Union, returned some mare basalts with even lower titanium, so they were dubbed "very-low-titanium" basalts. Most scientists figure that mare basalts have a complete range in titanium abundance. Data from the U. S. Clementine Mission confirm this, and show that the

Mineral abundances in mare basalts



high-titanium basalts are not really very common on the Moon.

The shapes of the mineral grains and how they are intergrown in mare basalts indicate that these rocks formed in lava flows, some thin (perhaps a meter thick), others thicker (up to perhaps 30 meters). This is not unusual for basalt flows on Earth. Many lunar mare basalts also contain holes, called vesicles, which were formed by gas bubbles trapped when the lava solidified. Earth basalts also have them. On Earth, the abundant gases escaping from the lava are carbon dioxide and water vapor, accompanied by some sulfur and chlorine gases. We are not as sure what gases escaped from lunar lavas, although we know that water vapor was not one of them because there are no hints for the presence of water or water-bearing minerals in any Moon rock. The best bet is a mixture of carbon dioxide and carbon monoxide, with some sulfur gases added for good measure.

On Earth, when the amount of gas dissolved in magma (the name for lava still underground) becomes large, it escapes violently and causes an explosive eruption. In places such as Hawai'i, for example, the lava erupts in large fountains up to several hundred meters high. The lava falls to the ground in small pieces, producing a pyroclastic deposit. This also happened on the Moon, producing the dark mantle deposits. One of these was sampled directly during the Apollo 17 mission. The sample, called the "orange soil," consists of numerous small orange glass beads. They are glass because they cooled rapidly, so there was not enough time to form and grow crystals in them.

Small samples of pyroclastic glasses were also found at other sites. Some are green, others yellow, still others red. The differences in color reflect the amount of titanium they contain. The green have the least (about 1 weight percent) and the red contain the most (14 weight percent), more than even the highest titanium basalt.

Experiments conducted on mare basalts and pyroclastic glasses show that they formed when the interior of the Moon partially melted. (Rocks do not have a single melting temperature like pure substances. Instead they melt over a range of temperatures: 1000–1200°C for some basalts, for example.) The experiments also show that the melting took place at depths ranging from 100 to 500 km, and that the rocks that partially melted contained mostly olivine and pyroxene, with some ilmenite in the regions that formed the high-titanium basalts. An involved but sensible chain of reasoning indicates that these deep rocks rich in olivine and pyroxene formed from the lunar magma ocean: while plagioclase floated to form anorthosites in the highlands crust, the denser minerals olivine and pyroxene sank. So, although the anorthosites and mare basalts differ drastically in age and composition, the origins are intimately connected.

What's next?

Scientists are still working on the bounty returned by the Apollo missions. New analytical techniques and improved understanding of how geological processes work keep the field exciting and vibrant. Eventually we will need additional samples and some extensive field work to fully understand the Moon and how it came to be and continues to evolve. These sampling and field expeditions will probably be done by a combination of robotic and piloted spacecraft.

In the meantime, Nature has provided a bonus: samples from the Moon come to us free of charge in the form of lunar meteorites. (See companion volume *Exploring Meteorite Mysteries*.) Thirteen separate meteorites have been identified so far, one found in Australia and the rest in Antarctica. We are sure that they come from the Moon on the basis of appearance and chemical and isotopic composition, but of course we do not know from where on the Moon they come. These samples have helped support the magma ocean idea. Most important, knowing that meteorites can be delivered to Earth by impacts on the Moon lends credence to the idea that we have some meteorites from Mars. The Martian

meteorites are collectively called SNC meteorites. If we did not know so much about the Moon we would never have been able to identify meteorites from the Moon, and, therefore, would not have been able to argue as convincingly that some meteorites come from Mars.

From the Moon, free of charge

The first lunar meteorite discovered in Antarctica hails from the lunar highlands and, like most highlands rocks, it is an impact breccia. The lunar meteorites prove that objects can be blasted off sizable objects without melting them, adding credence to the idea that a group of twelve meteorites comes from Mars.

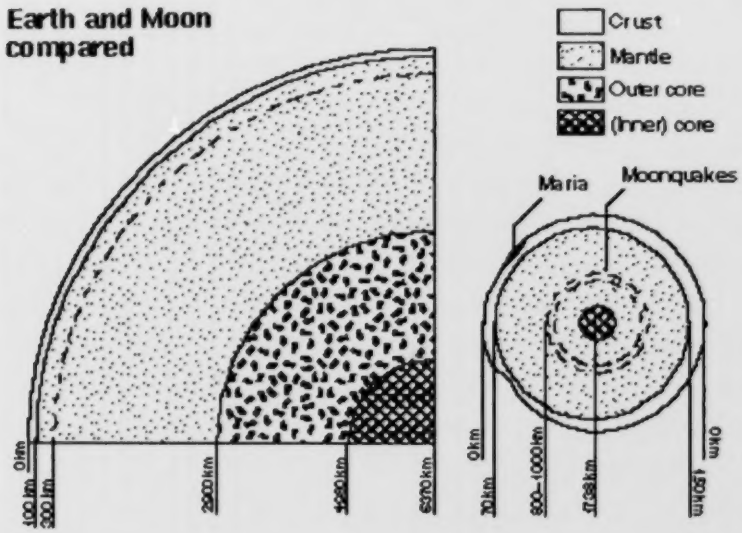
MOONQUAKES, THE MOON'S INTERIOR, AND THE MYSTERIOUS MAGNETIC FIELD

The Moon does not shake, rattle, and roll as Earth does. Almost all moonquakes are smaller than Earth's constant grumblings. The largest quakes reach only about magnitude 5 (strong enough to cause dishes to fall out of cabinets), and these occur about once a year. This is clear evidence that the Moon is not at present geologically active. No internal motions drive crustal plates as on Earth, or initiate hot spots to give rise to volcanic provinces like Hawai'i. This seismic inactivity is a wonderful virtue in the eyes of astronomers. Combined with the lack of an atmosphere to cause stars to twinkle, the low moonquake activity makes the Moon an ideal place to install telescopes.

We know about moonquakes from four seismometers set up by the Apollo missions. Besides telling us how many and how strong moonquakes are, the data acquired by the Apollo seismic network help us figure out something about the nature of the Moon's interior. On Earth, seismology has allowed us to know that the planet has a thin crust (20-60 km over continents, 8-10 km over ocean basins), a thick silicate mantle (down to 2900 km), and a large metallic iron core (2900 km to the center at 6370 km). The Moon is quite different. The crust is thicker than Earth's continental crust, ranging from 70 km on the Earth-facing side to perhaps 150 km on the farside. The mare basalts represent a thin veneer on this mostly plagioclase-rich crust, averaging only about 1 km in thickness (inferred mostly from photogeological studies). Evidence from samples collected on the rims of the large basins Imbrium and Serentatis and from remote sensing instruments carried onboard two Apollo missions, the Clementine Mission, and the forthcoming Lunar Prospector Mission suggest that the lower crust may not contain as much plagioclase as does the upper half of the crust. Beneath the crust is the lunar mantle, which is the largest part of the Moon. There might be a difference in rock types above and below a depth of 500 km, perhaps representing the depth of the lunar magma ocean. Beneath the mantle lies a small lunar core made of metallic iron. The size of the core is highly uncertain, with estimates ranging from about 100 km to 400 km.

That little core is important, though. The Moon does not have much of a magnetic field, so the lunar core is not generating magnetism the way Earth's core is. Nevertheless, it did in the past. Lunar rocks are magnetized, and the strength of the magnetic field has been measured by special techniques. Also, older rocks have stronger magnetism, suggesting that the Moon's magnetic field was stronger in the distant past, and then decreased to its weak present state. Why this happened is unknown. What is known is this: you cannot navigate around the Moon using a compass!

There are other mysteries about the Moon's magnetism. Although the field was always weak and is extremely weak now, there are small areas on the Moon that have magnetic fields much stronger than the surrounding regions. These magnetic anomalies have not been figured out. Some scientists have associated them with the effects of large, basin-forming impacts. Others have suggested that the



Inside the Moon and Earth

Scientists have learned what Earth and the Moon are like inside by several techniques, the most important of which is seismology, the study of earthquake (and, of course) moonquake waves. Earth has a much larger metallic core than does the Moon.

ionized gases produced when comets impact the Moon might give rise to strong magnetic anomalies in the crater ejecta. The jury is still out. The Lunar Prospector Mission will thoroughly map the distribution of magnetic anomalies, perhaps helping to solve this mystery.

THE MOON'S ORIGIN: A BIG WHACK ON THE GROWING EARTH

For a long time, the most elusive mystery about the Moon was how it formed. The problem baffled philosophers and scientists for hundreds of years. All of the hypotheses advanced for lunar origin had fatal flaws, even though partisans tried tenaciously to explain away the defects. The capture hypothesis, which depicts capture of a fully formed Moon by Earth, suffered from improbability. Close encounter with Earth would either result in a collision or fling the Moon into a different orbit around the Sun, probably never to meet up with Earth again. The fission hypothesis, in which the primitive Earth spins so fast that a blob flies off, could not explain how Earth got to be spinning so fast (once every 2.5 hours) and why Earth and the Moon no longer spin that fast. The double-planet hypothesis pictures Earth and the Moon forming together, a two-body system from the start. This idea has trouble explaining Earth's rotation rate and how the moon-forming material got into orbit around Earth and stayed there, rather than falling to Earth. (These problems with total amount of spinning involve both Earth's rotation and the Moon's motion around Earth. The amount of rotation and revolving is quantified by a physical property called angular momentum.) The problem was so frustrating that some scientists suggested that maybe science had proved that the Moon does not exist!

The annoying problems with the classical hypotheses of lunar origin led scientists to consider alternatives. This search led to the seemingly outlandish idea that the Moon formed when a projectile the size of the planet Mars (half Earth's radius and one-tenth its mass) smashed into Earth when it had grown to about 90% of its present size. The resulting explosion sent vast quantities of heated material into orbit around Earth, and the Moon formed from this debris. This new hypothesis, which blossomed in 1984 from seeds planted in the mid-1970s, is called the giant impact theory. It explains the way Earth spins and why Earth has a larger metallic core than does the Moon. Furthermore, modern theories for how the planets are assembled from smaller bodies, which were assembled from still smaller ones, predict that when Earth was almost done forming, there would have been a body nearby with a mass about one-tenth that of Earth. Thus, the giant impact hypothesized to have formed the Moon is not an implausible event. The chances are so high, in fact, that it might have been unavoidable.

One would think that an impact between an almost Earth-sized planet and a Mars-sized planet would be catastrophic. The energy involved is incomprehensible. Much more than a trillion trillion tons of material vaporized and melted. In some places in the cloud around the Earth, temperatures exceeded 10,000°C. A fledgling planet the size of Mars was incorporated into Earth, its metallic core

and all, never to be seen again. Yes, this sounds catastrophic. But out of it all, the Moon was created and Earth grew to almost its final size. Without this violent event early in the Solar System's history, there would be no Moon in Earth's sky, and Earth would not be rotating as fast as it is because the big impact spun it up. Days might even last a year. But then, maybe we would not be here to notice.

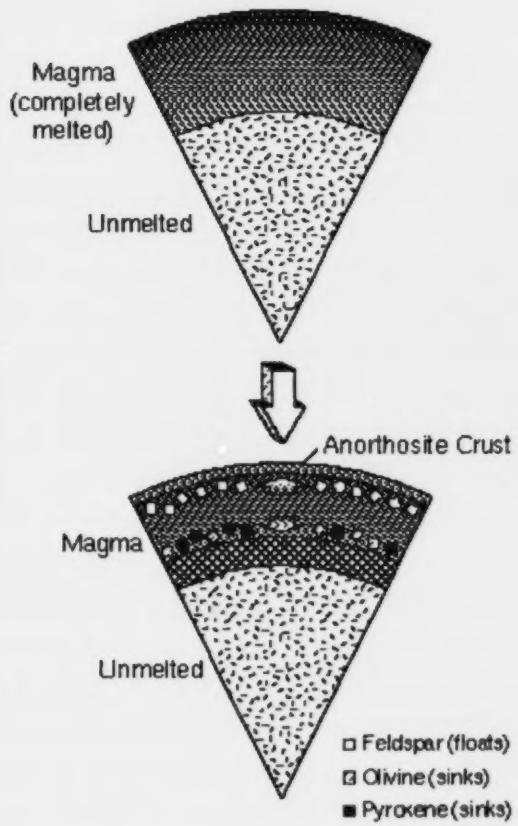
WHACK!

The Moon may have formed when an object the size of the planet Mars smashed into Earth when our future home was about 90% constructed. This fierce event made Earth larger and blasted off vaporized and melted material into orbit. The Moon formed from this debris. This painting was created by William K. Hartmann, one of the scientists who invented the giant impact hypothesis for lunar origin.

A BRIEF HISTORY OF THE MOON

We know the general outlines of what happened to the Moon after it was formed by a giant impact. The first notable event, which may have been a consequence of the giant impact, was the formation and crystallization of the magma ocean. Nobody knows how deep it was, but the best guess is that it was at least 500 km deep. The first minerals to form in this mind-boggling magmatic system were the iron and magnesium silicates olivine and pyroxene. They were denser than the magma, so they sank, like rocks in a pond, though not as fast. Eventually, plagioclase feldspar formed, and because it was less dense than the magma, began to float to the top, like bubbles in cola. It accumulated and produced mountains of anorthosite, producing the first lunar crust. The magma ocean phase ended by about 4.4 billion years ago. [See the "Differentiation" activity on Pages 57–60.]

The lunar magma ocean



Sinking and floating in an ocean of magma

Soon after it formed, the Moon was surrounded by a huge shell of molten rock called the lunar magma ocean. As crystals formed in it, the denser ones such as olivine and pyroxene sank and the less dense ones, such as feldspar, floated upwards, forming the original anorthosite crust on the Moon. Dropping toothpicks and pennies into a glass of water shows the process: the toothpicks (representing feldspar) float and the pennies (olivine and pyroxene) sink.

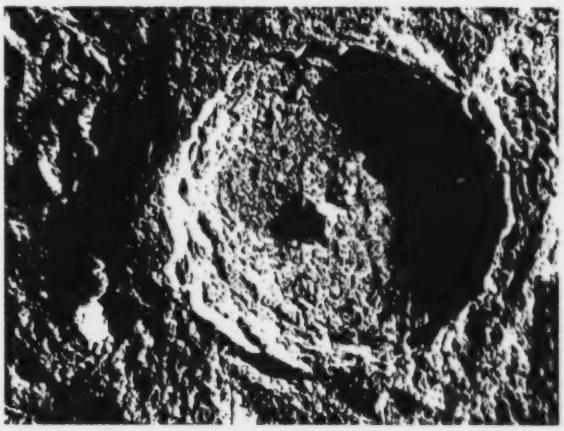
Almost as soon as the crust had formed, perhaps while it was still forming, other types of magmas that would form the norites and troctolites in the highlands crust began to form deep in the Moon. A great mystery is where inside the Moon and how deep. Many lunar specialists believe the magmas derived from unmelted Moon stuff beneath the magma ocean. In any case, these magmas rose and infiltrated the anorthosite crust, forming large and small rock bodies, and perhaps even erupting onto the surface. Some of the magmas reacted chemically with the dregs of the magma ocean (KREEP) and others may have dissolved some of the anorthosite. This period of lunar history ended about 4.0 billion years ago.

All during these first epochs, left-over projectiles continued to bombard the Moon, modifying the rocks soon after they formed. The crust was mixed to a depth of at least a few kilometers, perhaps as much as 20 km, as if a gigantic tractor had plowed the lunar crust. Though not yet proven, the rate of impact may have declined between 4.5 and 4.0 billion years ago, but then grew dramatically, producing most of the large basins visible on the Moon. This cataclysmic bombardment is postulated to have lasted from 4.0 to 3.85 billion years ago. [See the "Impact Craters" activity on Pages 61–70, and the "Regolith Formation" activity on Pages 47–52.]

Once the bombardment rate had settled down, the maria could form. Basalts like those making up the dark mare surfaces formed before 3.85 billion years ago, but not as voluminously as later, and the enormous bombardment rate demolished whatever lava plains formed. However, between 3.7 and about 2.5 billion years ago (the lower limit is highly uncertain), lavas flowed across the lunar surface, forming the maria and decorating the Moon's face. Along with the basalts came pyroclastic eruptions, high fountains of fire that launched glowing droplets of molten basalt on flights up to a few hundred kilometers.

Since mare volcanism ceased, impact has been the only geological force at work on the Moon. Some impressive craters have been made, such as Copernicus (90 km across) and Tycho (85 km). These flung bright rays of material across the dark lunar landscape, adding more decoration. In fact, some of the material blasted from Tycho caused a debris slide at what would become the Apollo 17 landing site. Samples from this site indicate that the landslide and some associated craters formed about 110 million years ago. This, therefore, is the age of the crater Tycho. It is a triumph of geological savvy that we were able to date an impact crater that lies over 2000 km from the place we landed!

The impacts during the past billions of years also have mixed the upper several meters of crust to make the powdery lunar regolith. The Sun has continued to implant a tiny amount of itself into the regolith, giving us its cryptic record and providing resources for future explorers. And recently, only seconds ago in geologic time, a few interplanetary travelers left their footprints here and there on the dusty ground.



Anatomy of an impact crater

The crater Tycho in the southern highlands on the lunar nearside is 85 kilometers across. Its terraced walls rise 3 to 4 kilometers above its floor. Its rim rises above the surrounding terrain, and its floor sits below it. Smooth material on the floor of the crater consists of impact-melted rock that flowed like lava across the growing floor in the later stages of excavation. In response to the huge increase then decrease in pressure, mountains two kilometers high rose from its floor, bringing up material from as much as ten kilometers in the crust. The blanket of material surrounding the crater is called the ejecta blanket; this pile of debris becomes progressively thinner away from the crater (especially evident on the left of the photo).

Although not visible on this photograph, large craters like Tycho also have rays emanating from them. Rays form when materials thrown out of the crater land and excavate more of the lunar landscape along arcuate paths. The Tycho event caused a landslide and several secondary impacts at the Apollo 17 landing site, over 2000 kilometers away. Analysis of samples collected during the Apollo 17 mission indicates that these events took place 110 million years ago. Thus, Tycho formed 110 million years ago.

THE MOON AND EARTH: INEXORABLY INTERTWINED

The Moon ought to be especially alluring to people curious about Earth. The two bodies formed near each other, formed mantles and crusts early, shared the same post-formational bombardment, and have been bathed in the same flux of sunlight and solar particles for the past 4.5 billion years. Here are a few examples of the surprising ways in which lunar science can contribute to understanding how Earth works and to unraveling its geological history.

Origin of the Earth-Moon System. No matter how the Moon formed, its creation must have had dramatic effects on Earth. Although most scientists have concluded that the Moon formed as a result of an enormous impact onto the growing Earth, we do not know much about the details of that stupendous event. We do not know if the Moon was made mostly from Earth materials or mostly projectile, the kinds of chemical reactions that would have taken place in the melt-vapor cloud, and precisely how the Moon was assembled from this cloud.

Magma oceans. The concept that the Moon had a magma ocean has been a central tenet of lunar science since it sprung from fertile minds after the return of the first lunar samples in 1969. It is now being applied to Earth, Mars, and asteroids. This view of the early stages of planet development is vastly different from the view in the 1950s and 1960s. Back then, most (not all) scientists believed the planets assembled cold, and then heated up. The realization that the Moon had a magma ocean changed all that and has led to a whole new way of looking at Earth's earliest history.

Early bombardment history of Earth and Moon. The thousands of craters on the Moon's surface chronicle the impact record of Earth. Most of the craters formed before 3.9 billion years ago. Some scientists argue that the Moon suffered a cataclysmic bombardment (a drastic increase in the number of impacting projectiles) between 3.85 and 4.0 billion years ago. If this happened and Earth was subjected to the blitzkrieg as well, then development of Earth's earliest crust would have been affected. The intense bombardment could also have influenced the development of life, perhaps delaying its appearance.

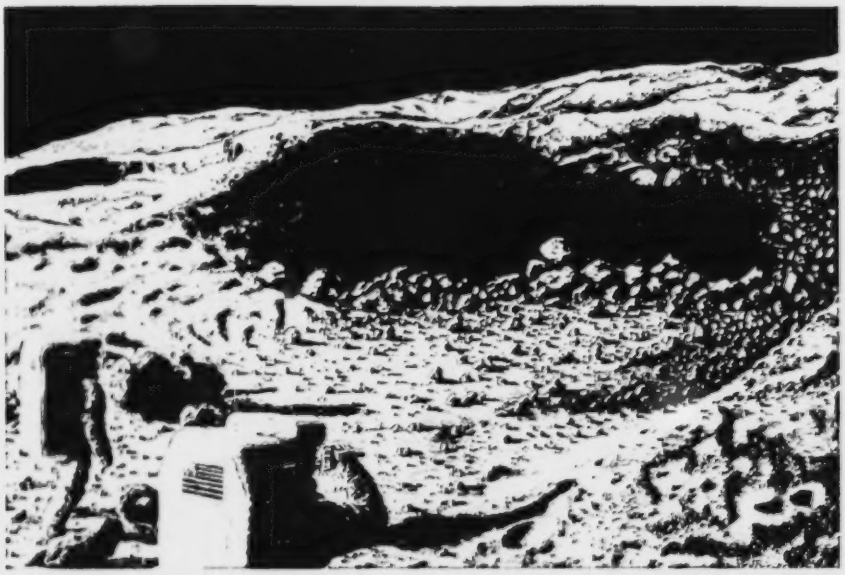
Impacts, extinctions, and the evolution of life on Earth. The mechanisms of evolution and mass extinctions are not understood. One possibility is that some mass-extinction events were caused by periodic increases in the rate of impact on Earth. For example, the mass extinctions, which included the demise of the dinosaurs, at the end of the Cretaceous period (65 million years ago), may have been caused by a large impact event. Attempts to test the idea by dating impact craters on Earth are doomed because there are too few of them. But the Moon has plenty of craters formed during the past 600 million years (the period for which we have a rich fossil record). These could be dated and the reality of spikes in the impact record could be tested.

How geologic processes operate. The Moon is a natural laboratory for the study of some of the geologic processes that have shaped Earth. It is a great place to study the details of how impact craters form because there are so many well-preserved craters in an enormous range of sizes. It is also one of the places where volcanism has operated, but at lower gravity than on either Earth or Mars.

LIFE AND WORK AT A MOON BASE

People will someday return to the Moon. When they do, it will be to stay. They will build a base on the Moon, the first settlement in the beginning of an interplanetary migration that will eventually take them throughout the Solar System.

There will be lots to do at a lunar base. Geologists will study the Moon with the intensity and vigor they do on Earth, with emphasis on field studies. Astronomers will make magnificent observations of the universe. Solar scientists will study the solar wind directly and investigate past activity trapped in layers of regolith. Writers and artists will be inspired by a landscape so different from Earth's. Life scientists will study how people adapt to a gravity field one-sixth as strong as Earth's, and figure out how to grow plants in lunar greenhouses. Engineers will investigate how to keep a complex facility operating continuously in a hostile environment. Mining and chemical engineers will determine how to extract resources from Moon rocks and regolith. The seemingly dry lunar surface contains plenty of the ingredients to support life at a Moon base (oxygen and hydrogen for water, nitrogen and carbon for the growth of plants), including the construction



Geology at a Moon Base

The best geology is done in the field. To understand rocks we must examine them up close, map their distributions, see the structures in them, and chip off samples when necessary. The field geology done during the Apollo missions was hampered by the lack of time the astronauts could devote to it. But that will change when people live permanently on the Moon. Geologists will be able to spend as much time as they need to decipher the story recorded by lunar rock formations. This painting shows three astronauts (one in the distance) examining the outside of a lava tube, an underground conduit that carried red-hot lava to an eruption site perhaps hundreds of kilometers away.

materials to build and maintain the base (regolith can be molded into bricks; iron, titanium, and aluminum can be smelted and forged into tools and building materials). It will be an exciting, high-tech, faraway place inhabited by adventurous souls. [See the Unit 3 activities beginning on Page 99.]

WHERE MOON ROCKS HANG OUT

Since arrival on Earth, lunar samples have been treated with the respect they deserve. Most of the treasure of Apollo is stored at the Lunar Curatorial Facility at the Johnson Space Center, Houston, Texas. A small percentage is stored in an auxiliary facility at Brooks Air Force Base near San Antonio, Texas, placed there in case a disaster, such as a hurricane, befalls Houston and the samples are destroyed. Many small samples are also in the laboratories of investigators around the world, where enthusiastic scientists keep trying to wring out the Moon's secrets.

The Curatorial Facility is one of the cleanest places you'll ever see. To go inside, you must wear white suits, boots, hats, and gloves, outfits affectionately known as "bunny suits." Wipe a gloved hand on a stainless steel cabinet and you will not find a trace of dust because the air is filtered to remove potential contaminating particles.

The samples are stored in a large vault, and only one at a time is moved to a glove box. You can pick up the rocks by jamming your hands into a pair of the black rubber gloves, allowing you to turn a rock over, to sense its mass and density, to connect with it. A stereomicroscope allows you to look at it closely. If you decide you need a sample, and of course you have been approved to obtain one, then expert lunar sample processors take over. The sample is photographed before and after the new sample is chipped off. This is time consuming, but valuable to be sure we know the relationships of all samples to each other. In many cases, we can determine the orientation a specific part of a rock was in on the surface of the Moon before collection.

A select small number of pieces of the Moon are on display in public museums, and only three pieces can actually be touched. These so-called lunar "touchstones" were all cut from the same Apollo 17 basaltic rock. One touchstone is housed at the Smithsonian Air and Space Museum in Washington, D.C. Another touchstone is at the Space Center Houston facility adjacent to the Johnson Space Center. A third touchstone is on long-term loan to the Museo de Las Ciencias at the Universidad Nacional Autonoma de Mexico. Visitors to these exhibits marvel at the unique experience of touching a piece of the Moon with their bare hands.

Safe haven for precious rocks

NASA stores the lunar sample collection in a specially constructed facility called the Lunar Curatorial Facility at the Johnson Space Center in Houston, Texas. The priceless materials remain in a nitrogen atmosphere, which is far less reactive chemically than normal oxygen-rich air. Scientists working in the facility wear lint-free outfits affectionately known as "bunny suits," and handle the samples in glove boxes. In this photograph, Roberta Score is examining a piece of an Apollo 16 rock, while Andrea Mosie (left) looks on.

SCIENTISTS AS POETS

Scientists do not view the world in purely objective ways. Each has biases and a unique way of looking at the world. Science is not done solely with piles of data, hundreds of graphs, or pages of equations. It is done with the heart and soul, too. Sometimes a scientist is moved to write about it in elegant prose like that written by Loren Eisley or in poetry, like the poem written by Professor Carlé Pieters of Brown University. Dr. Pieters holds her doctorate from MIT and is an expert in remote sensing of planetary surfaces. She is especially well known for her telescopic observations of the Moon. The poem first appeared in the frontispiece of Origin of the Moon, published by the Lunar and Planetary Institute.

The Original Moon

Four and a half æons ago
a dark, dusty cloud deformed.
Sun became star; Earth became large,
and Moon, a new world, was born.

This Earth/Moon pair, once linked so close,
would later be forced apart.
Images of young intimate ties
we only perceive in part.

Both Earth and Moon were strongly stripped
of their mantle siderophiles.
But Moon alone was doomed to thirst
from depletion of volatiles.

Moon holds secrets of ages past
when planets dueled for space.
As primordial crust evolved
raw violence reworked Moon's face.

After the first half billion years
huge permanent scars appeared;
ancient feldspathic crust survived
with a mafic mantle mirror.

But then there grew from half-lived depths
a new warmth set free inside.
Rivers and floods of partial melt
resurfaced the low 'frontside'.

Thus evolved the Original Moon
in those turbulent times.
Now we paint from fragments of clues
the reasons and the rhymes:

Sister planet;
Modified clone;
Captured migrant;
Big splash disowned?

The Truth in some or all of these
will tickle, delight,
temper, and tease.

— Carlé Pieters

Moon ABCs Fact Sheet

Property	Earth	Moon	Brain Busters
Equatorial diameter	12,756 km	3,476 km	How long would it take to drive around the Moon's equator at 80 km per hour?
Surface area	510 million square km	37.8 million square km	The Moon's surface area is similar to that of one of Earth's continents. Which one?
Mass	5.98×10^{24} kg	7.35×10^{22} kg	What percentage of Earth's mass is the Moon's mass?
Volume	---	---	Can you calculate the volumes of Earth and the Moon?
Density	5.52 grams per cubic cm	3.34 grams per cubic cm	Check this by calculating the density from the mass and volume.
Surface gravity	9.8 m/sec/sec	1.63 m/sec/sec	What fraction of Earth's gravity is the Moon's gravity?
Crust	Silicate rocks. Continents dominated by granites. Ocean crust dominated by basalt.	Silicate rocks. Highlands dominated by feldspar-rich rocks and maria by basalt.	What portion of each body is crust?
Mantle	Silicate rocks dominated by minerals containing iron and magnesium.	Similar to Earth.	Collect some silicate rocks and determine the density. Is the density greater or lesser than the Earth/Moon's density? Why?

Moon ABCs Fact Sheet

Property	Earth	Moon	Brain Busters
Core	Iron, nickel metal	Same, but core is much smaller	What portion of each body is core?
Sediment or Regolith	Silicon and oxygen bound in minerals that contain water, plus organic materials.	Silicon and oxygen bound in minerals, glass produced by meteorite impacts, small amounts of gases (e.g., hydrogen) implanted by the solar wind. No water or organic materials.	Do you think life ever existed on the Moon? Why or why not?
Atmosphere (main constituents)	78 % nitrogen, 21 % oxygen	Basically none. Some carbon gases (CO_2, CO, and methane), but very little of them. Pressure is about one-trillionth of Earth's atmospheric pressure.	Could you breathe the lunar atmosphere?
Length of day (sidereal rotation period)	23.93 hours	27.3 Earth days	How long does daylight last on the Moon?
Surface temperature	Air temperature ranges from -88°C (winter in polar regions) to 58°C (summer in tropical regions).	Surface temperature ranges from -193°C (night in polar regions) to 111°C (day in equatorial regions).	Why are the temperatures of Earth and the Moon so different?
Surface features	25 % land (seven continents) with varied terrain of mountains, plains, river valleys. Ocean floor characterized by mountains, plains.	84 % heavily-cratered highlands. 16 % basalt-covered maria. Impact craters--some with bright rays, crater chains, and rilles.	Compare maps of Earth and the Moon. Is there any evidence that plate tectonics operated on the Moon?

Rock ABCs Fact Sheet

What are minerals?

Minerals are naturally occurring solids that have definite chemical compositions and are crystalline. Crystals are individual pieces of minerals. The most important characteristic of crystals is the orderly internal arrangement of atoms. This internal order causes the beautiful crystal shapes.

MINERAL	ELEMENTS	APPEARANCE IN MOON ROCKS
Plagioclase feldspar	calcium (Ca), aluminum, silicon (Si), Oxygen (O)	Whitish to translucent grayish; usually occurs as grains longer than they are wide.
Pyroxene	iron (Fe), magnesium, (Mg), calcium (Ca), silicon (Si), oxygen (O)	Brown to black; grains usually longer than wide in mare basalts, somewhat squarish in highland rocks.
Olivine	iron (Fe), magnesium (Mg), silicon (Si), oxygen (O)	Greenish; usually occurs as roundish crystals.
Ilmenite	iron (Fe), titanium (Ti), oxygen (O)	Black, elongated to squarish crystals.

What are rocks?

Rocks are naturally occurring solids composed of one or more minerals. At least two abundant minerals usually occur in a rock, along with several others. The minerals are intergrown in intricate ways that depend on how the rock formed. Rocks are classified on the basis of the abundance of the minerals they contain, sizes of individual crystals, and the process that formed the rocks.

Approximate mineral abundances (percents) in Moon rocks

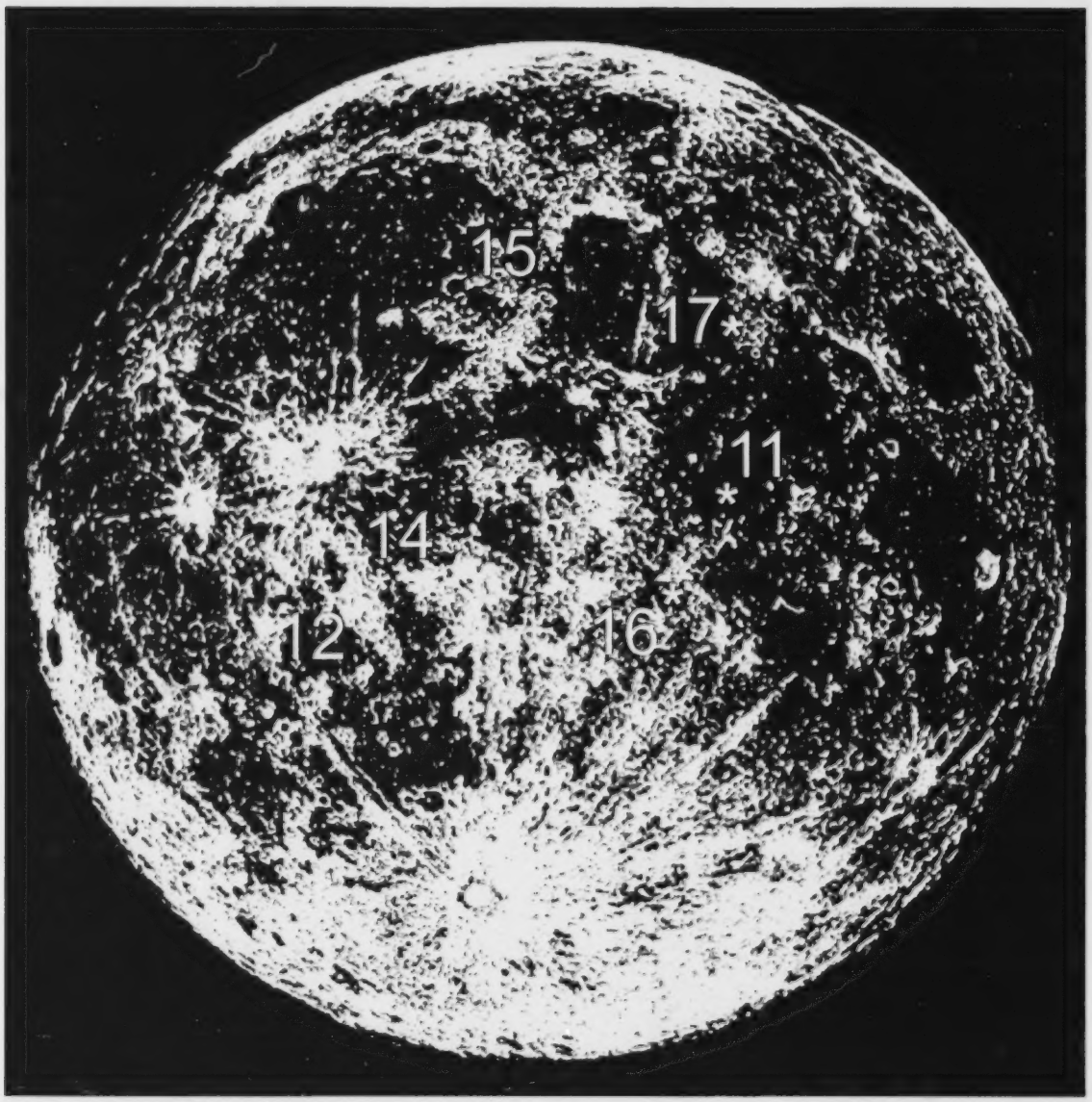
	Plagioclase	Pyroxene	Olivine	Ilmenite
Highland rocks				
Anorthosite	90%	5%	5%	0%
Norite	60%	35%	5%	0%
Troctolite	60%	5%	35%	0%
Mare basalts				
High-titanium	30%	54%	3%	18%
Low-titanium	30%	60%	5%	5%
Very-low titanium	35%	55%	8%	2%

Progress in Lunar Science

Topic	1959 View	Early 1969 View	Post-Apollo View 1975	1997 View
Surface Material	Volcanic ash, impact debris, fluffy dust.	Probably impact debris, but other ideas not ruled out.	Impact debris derived from underlying rock layer or bare rock?	Regolith formation now modeled by computer.
Craters	Impact or volcanic?	Majority impact; unknown percentage of volcanic origin.	Almost all impact; many rocks affected by impacts.	More is known about how material is thrown out of a growing crater.
Maria	Impact or volcanic?	Probably volcanic.	Definitely volcanic.	Better understanding of eruption conditions.
Composition of Maria	Unknown	Probably basalt.	Definitely basalt.	Wide variety of basalt types.
Composition of Highlands	Unknown	Probably rocks with more aluminum and less iron than mare basalt.	Rocks high in aluminum with large percentages of feldspar.	Wide variety of rock types, but all containing more aluminum than mare basalt.
Composition of Farside	Unknown	Mare areas less abundant than on the nearside.	Highlands similar to nearside highlands.	Highlands containing rocks rich in aluminum.
Composition of Mantle	Unknown	No progress.	High content of olivine and pyroxene.	Amounts and composition of olivine and pyroxene vary.
Nature of Core	Smaller than Earth's.	No progress.	Smaller than 500 km.	Smaller than 250 km.
Volatiles (such as water) and Organic Compounds	Unknown, though some scientists thought water had flowed on Moon's surface.	No progress.	Moon contains no water or organic compounds, and other volatiles much lower than on Earth.	There might be water brought in by comets and trapped in very cold places at the South Pole.
Rock Ages	Unknown	Uncertain, but probably ancient (more than a few billion years).	Highlands: older than 3.9 billion years. Maria: 3.2 - 3.7 billion years.	Highlands: most igneous rocks older than 4.1 billion years, with anorthosites 4.4 billion years. Maria: some as young as about 2 billion years others as old as 4.3 billion years.
Magma Ocean	Not even conceived.	No progress.	Highlands formed from huge magma system more than 300km deep.	Anorthosites formed from magma ocean; other highland rocks formed after that.
Origin	Captured, derived from Earth, or dual planet?	No progress.	Moon and Earth probably related, so capture idea less likely.	Giant impact on Earth, followed by formation of Moon in Earth orbit.

Nearside of the Moon

Apollo Landing Sites



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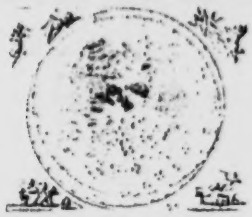
Unit 1



Pre-Apollo Activities

Distance to the Moon
Diameter of the Moon
Reaping Rocks

Before Apollo 11 astronauts Neil A. Armstrong and Edwin E. "Buzz" Aldrin Jr. stepped on the Moon on July 20, 1969, people had studied the Moon by eye, telescope, and images from spacecraft. The theme of Unit 1 is a basic introduction to the Moon -- how it looks from Earth, how far away it is, and how big it is. The activities allow students to make comparisons between the Moon and Earth as well as to make predictions about the Moon rocks.

Encourage students to sketch and describe nightly observations of the Moon and keep a written record of date and time. Nightly charting of the Moon helps students recognize Moon phases as well as the bright and dark terrains.

Scale models and proportional relationships are featured in the first two activities. The "Distance to the Moon" and "Diameter of the Moon" activities introduce students to techniques of measuring distances in space indirectly.

This unit also includes an activity to collect and study rocks called "Reaping Rocks." This activity should follow a more comprehensive lesson on basic rock and mineral identification. The activity also extends learning to the Moon and asks students to predict how their rock collections will compare with lunar samples.

A Resource Section for Unit 1 is on Page 24.

Unit 1

Resource Section

This list presents possible independent and commercial sources of items to complement the activities in Unit 1. The sources are offered without recommendation or endorsement by NASA. Inquiries should be made directly to the appropriate source to determine availability, cost, and ordering information before sending money. Contact your NASA Educator Resource Center (see Page 146) for more lists of resources available directly from the National Aeronautics and Space Administration.

Maps

The Earth's Moon by National Geographic Society. Wall map showing nearside and farside. Also includes graphics with captions explaining eclipses, lunar phases, tides, and other phenomena. U.S. and Soviet landing/impact sites are shown. The reverse side has an index of lunar named features and selected photographs from the Apollo missions.
National Geographic Society
Educational Services, Department 91
Washington, D.C. 20036
1-800-368-2728 or FAX 1-301-921-1575

Giant Moon Map by Rand McNally. Wall map showing the nearside. Contact Rand McNally directly, or order it through:
Astronomical Society of the Pacific
390 Ashton Ave.
San Francisco, CA 94112
1-415-337-2624

Maps of Earth, Moon, Mars, etc.
U.S. Geological Survey Map Sales
Box 25286
Denver Federal Center
Denver, CO 80225
303-236-7477
(Ask for Customer Service)

Globes

Edmund Scientific Co.
101 E. Gloucester Pike
Barrington, NJ 08007-1380
1-609-573-6270 or FAX 1-609-573-6295

Lunar Phase Calendars

Celestial Products
P.O. Box 801
Middleburg, VA 22117
1-800-235-3783 or FAX 1-703-338-4042

Earth Rock Sample Sets

Ward's Natural Science Establishment, Inc.
P.O. Box 92912
Rochester, NY 14692-9012
1-800-962-2660

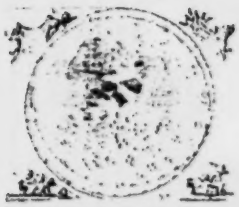
Slides

Glorious Eclipses slide set
Astronomical Society of the Pacific
390 Ashton Ave.
San Francisco, CA 94112
1-415-337-2624

Other Teacher's Guides

Exploring Meteorite Mysteries: Teacher's Guide with Activities, NASA EG-1997-08-104-HQ.
M. Lindstrom et. al., 1997
Companion volume available from NASA Educator Resource Centers or CORE (refer to Page 146 of this book.)

Return to the Moon: Moon Activities Teacher's Guide, 1990
Challenger Center for Space Science Education
1101 King Street, Suite 190
Alexandria, VA 22314
1-703-683-9740



Distance to the Moon

Purpose

To calculate the distance between scale models of Earth and the Moon.

Background

As long as people have looked at the Moon, they have wondered how far away it is from Earth. The average distance to the Moon is 382,500 km. The distance varies because the Moon travels around Earth in an elliptical orbit. At perigee, the point at which the Moon is closest to Earth, the distance is approximately 360,000 km. At apogee, the point at which the Moon is farthest from Earth, the distance is approximately 405,000 km.

Distance from Earth to the Moon for a given date can be obtained by asking a local planetarium staff. Students interested in astronomy may enjoy looking at *The Astronomical Almanac* printed yearly by the U.S. Government printing office. When the Apollo 11 crew landed on the Moon on July 20, 1969, they were 393,309 km away from home.

In this activity students will use simple sports balls as **scale** models of Earth and the Moon. Given the astronomical distance between Earth and the Moon, students will determine the scale of the model system and the distance that must separate the two models.

The "Moon ABCs Fact Sheet" lists the Earth's diameter as 12,756 km and the Moon's diameter as 3,476 km. Therefore, the Moon's diameter is 27.25% of Earth's diameter. An official basketball has a diameter of 24 cm. This can serve as a model for Earth. A tennis ball has a diameter of 6.9 cm which is close to 27.25% of the basketball. (The tennis ball is actually 28.8% the size of the basketball.) These values are very close to the size relationship between Earth and the Moon. The tennis ball, therefore, can be used as a model of the Moon.

The scale of the model system is determined by setting the diameter of the basketball equal to the diameter of Earth. This is written as a simple relationship shown below:

$$24 \text{ cm} = 12{,}756 \text{ km}$$

Expressed more simply, 1 cm in the model system equals 531.5 km in space:

$$1 \text{ cm} = 531.5 \text{ km}$$

Distance to the Moon

Using this scale, the basketball-tennis ball separation in centimeters (**x**) is derived:

$$x = \frac{382{,}500 \text{ km}}{531.5 \text{ km}} = 719.7 \text{ cm}$$

The value **x** may be rounded to 720 cm and converted to meters so that the students need to place the basketball and tennis ball 7.2 m apart.

Preparation

Review and prepare materials listed on the student sheet.
If it is not possible to obtain an official-size basketball and tennis ball, then you can use other spherical objects or circles drawn on paper. Clay balls may be used as models. For example, for two clay balls, 10 cm diameter and 2.7 cm diameter, the scale is 1 cm = 1,275.6 km. At this scale, students need to separate the clay balls by 3 m.

In Class

Divide the students into cooperative groups. Students must keep track of units of measure.

Wrap Up

Did the students have an accurate idea of the size relationship between Earth and the Moon before doing this activity?

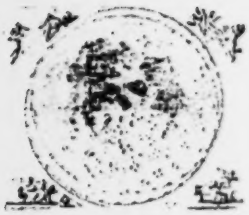
Did the effect of separating the scale models help them visualize the distance to the Moon?

Extensions

1. How long did it take Apollo astronauts to travel to the Moon?

2. Have students measure the circumferences of various spheres so that each group uses a different pair of models.

3. Instead of using the average distance to the Moon, use the distance from July 20, 1969, to recall the Apollo 11 landing or use the distance for today.



Distance to the Moon

Purpose

To calculate the distance between scale models of Earth and the Moon.

Key Word

scale

Materials

"Moon ABCs Fact Sheet"

sports balls

calculator

meter tape

Procedure

1. If Earth were the size of an official basketball, then the Moon would be the size of: another basketball? soccer ball? baseball? tennis ball? golf ball? marble?

2. The diameter of Earth in kilometers is:

3. The diameter of the Moon in kilometers is:

4. What percentage of Earth's diameter is the Moon's diameter?

5. Use the list below to change or confirm your answer to Question 1.

	diameter in cm
official basketball	24
size 5 soccer ball	22
official baseball	7.3
tennis ball	6.9
golf ball	4.3
marble	0.6

If Earth is a basketball, then the Moon is a:

Distance to the Moon

6. Use an official basketball as a model of Earth. Use a second ball, the one you determined from Question 5, as a model of the Moon.

7. Determine the scale of your model system by setting the diameter of the basketball equal to the diameter of Earth.

_____cm = _____km therefore,

1 cm = [ ] km

8. If the distance to the Moon from Earth is 382,500 km, then how far apart must you separate the two scale models to accurately depict the Earth/Moon system?

Using the scale value in the box from Step 7, the model separation in centimeters (**x**) is derived:

$$\mathbf{x} = \frac{\text{actual distance to the Moon in kilometers}}{\text{scale value in kilometers}}$$

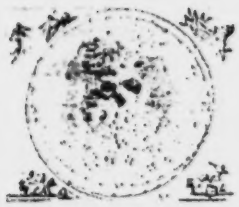
$$x = \frac{\boxed{}}{\boxed{}}$$

x = _____centimeters

The two scale models must be separated by _____ meters.

9. Set up your scale model of the Earth/Moon system. Does it fit in your classroom?

_____



Diameter of the Moon

Purpose

To calculate the diameter of the Moon using proportions.

Background

The diameter of the Moon is proportional to the diameter of a cardboard disk, given that you know the distance to the Moon and the distance to the cardboard disk.
The relationship is:

$$\frac{d}{l} = \frac{D}{L}$$

so that:

$$D = L(d/l)$$

where **D** = diameter of Moon
d = diameter of cardboard disk
L = distance to Moon
l = distance to cardboard disk

In this activity, students will measure **d** and **l**. They will be given **L**.
They will calculate **D**.

The diameter of the Moon (**D**) is 3,476 km.

Preparation

Review and prepare materials listed on the student sheet.
Choose a day and location for this activity which is best for viewing a full Moon.

A cardboard disk of 2 cm diameter works well. Better accuracy may be achieved by using a larger disk, thus a greater distance **l**. However, if obtaining or cutting cardboard is difficult, then this activity can also be done with dimes. A dime held out at arm's length will cover the Moon.

The distance from Earth to the Moon for a given date can be obtained by asking a local planetarium staff, Or for this activity, students may use an average value of 382,500 km.

Diameter of the Moon

In Class

If students work in pairs, then one student can use the string to measure distance from their partner's eye to the disk.

The same units do not have to be used on both sides of the equation, but **d** and **l** have to be the same units. The **D** will be the same unit as **L**.

Wrap-Up

To compute the density of the Moon use the diameter to compute volume and use the mass value of 7.35×10^{22} kg.

Density of the Moon is 3.34 grams/cubic cm.

7. How does water contribute to regolith formation on Earth?

Regolith formation on the Moon
Procedure C

1. Do you think regolith on the Moon is formed in the same manner as on Earth? Why or why not?

Now we will investigate the effects of meteoritic bombardment on regolith formation.

2. In a small **pan**, place 2 slices of **toasted white bread** onto 3 slices of **toasted golden wheat bread**. This represents the Moon's crust.

3. Drop a **rock** onto the layers of toasted bread twice. Describe the bread slices and the crumbs.

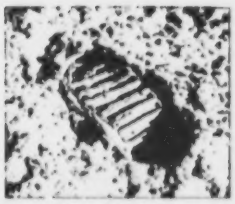
Regolith Formation

4. Drop the rock 20 times onto the layers of toasted bread. Describe the bread slices and the crumbs.

5. Which crumbs can be seen at the surface? Why?

6. How does the thickness of the crumb layers compare after 2 hits and after 20 more hits?

7. How does meteoritic bombardment make regolith on the Moon?



Lunar Surface

Purpose

To make a model of the Moon's surface and to consider the geologic processes and rocks of each area.

Background [also see "Teacher's Guide" Pages 2, 3, 4, 12, 13]

A variety of features are evident on the lunar surface. These features include **craters** with and without **rays** (also see the "Impact Craters" activity on Page 61), **crater chains**, **maria**, **rilles**, and **mountains**.

crater chains - in curved paths are probably incompletely formed rilles,

- in straight paths are probably from rocks thrown out during an impact event and landing in a row.

rilles - are long valleys crossing maria that formed as underground lava channels which collapsed after the hot lava flowed away.

mountains - almost all in the highlands are the rims of large craters,

- also occur in the centers of craters that are larger than 40 km diameter; these mountains are called central uplifts,

- also occur as low, circular, rounded hills called domes.

In this activity students will use clay, plaster of Paris, or playdough to construct model surfaces to match what they see on maps and photographs of the Moon. They "flag" Apollo landing sites and consider the collection site of each Lunar Disk sample.

Preparation

Review and prepare materials listed on the student sheet.
Obtain one or more lunar maps. Students can either be assigned to or given a choice of specific areas to model. Using maps of both the nearside (Earth-facing side) and farside of the Moon will give more variety of surface features.

Collect trays or shallow cardboard boxes and modeling material (recipes for playdough appear on Page 78). Assemble sculpturing tools such as wooden sticks, plastic knives, rolling pins, etc.

Lunar Surface

It is beneficial to do "The Lunar Disk" activity (on Page 39) first so students can relate the samples to their model surfaces.

In Class

Consider having cooperative teams build one model surface. Each team is responsible for describing the surface features, explaining the geology, and listing the typical rock types of the area. Either draw an outline around each area on a Moon map or if you have an extra map, cut the map into sections. The whole map is finally recreated by putting the model surfaces back together.

Have the students use toothpick flags to label Apollo landing sites.

Wrap-up

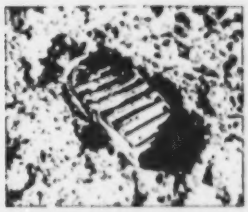
Review the variety of surface features found on the Moon. Are some features more common than others?

What are the most common terrains on the Moon? Do these terrains exist on the nearside, farside, or globally?

Review the processes that made the various surface features. Also see the "Impact Craters" activity on Page 61 and the "Clay Lava Flows" activity on page 71.

What kinds of rocks are found in the areas modeled by the students? Also see the "Apollo Landing Sites" activity on page 43 and the literature which accompanies the Lunar Sample Disk.

If the student teams made models of different sections of a large map, then did the modeled surface features match from tray to adjacent tray? Have the students discuss why or why not.



Lunar Surface

Purpose

To make a model of the Moon's surface and to consider the geologic processes and rocks of each area.

Key Words

crater
mountain
rille
mare
crater chain
ray
terrain

Materials

binoculars or telescope
lunar map
photographs of the Moon
clay, plaster of Paris, or playdough
tray
sculpturing tools
toothpick flags
Lunar Sample Disk

Procedure

1. Observe the Moon using **binoculars** or a **telescope**. What surface features can you see?

2. Look at a **map** and **photographs** of the Moon. List the many different features you see.

3. Prepare a model lunar surface by placing a thin, even layer of **modeling material** on a **tray**.

4. Use **sculpturing tools** to form the features that you see on the Moon's surface.

Lunar Surface

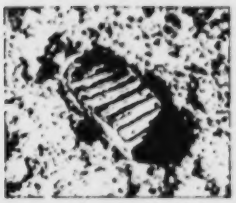
5. How do you think these surface features were created on the Moon? List at least one idea for each kind of feature.

11

6. If your model surface has an Apollo landing site, then label it with a **toothpick flag**.

7. What kinds of rocks occur in your area? If your area has an Apollo landing site, then include the names of samples from the **Lunar Sample Disk** in your answer.

8. Compare your model surface with your classmates' surfaces. Can you match features from one area to another? Why or why not?



Differentiation

Purpose

To see how minerals separate from each other in a magma ocean.

Background [also see "Teacher's Guide" Page 12]

When planets begin to melt, the materials in them begin to separate from one another. The heaviest materials, such as metallic iron, sink to form **cores**. Low density magmas rise forming **crusts**. This process is called **differentiation**.

Soon after formation, the Moon melted substantially forming a large body of **magma** that completely surrounded it. This is called the **lunar magma ocean**. The main evidence that this actually happened on the Moon is the presence of large amounts of the **mineral plagioclase feldspar** in the ancient, lunar **highlands** crust. Scientists surmise feldspar floated in the magma ocean and accumulated at the top, while denser minerals such as olivine and pyroxene sank and accumulated at the base of the magma ocean.

This same process happens in lava lakes and in magma chambers beneath **volcanoes** on Earth. Minerals denser than the melt sink; those less dense float. It is an important geological process that leads to the production of a wide variety of **igneous rocks**.

Preparation

Review and prepare materials listed on the student sheet. Students will simulate the process of differentiation using readily-available materials: water, a transparent container (1000-milliliter beakers are good because they look scientific, but any wide-mouthed glass will work), pennies or metal shot, sand, and toothpicks.

In Class

Take a handful of pennies, sand, and toothpicks and dump them into the water. The pennies (or metal shot) sink faster than the sand. The toothpicks float. The floating toothpicks lie at a variety of angles and are analogous to the feldspar that formed the initial lunar crust. There ought to be more pennies than sand on the very bottom, with sand on top of that pile. (The pennies are much denser, 8.9 grams per cubic centimeter, than the sand, about 2.6 grams per cubic centimeter, so the pennies sink faster.) The clear water in between represents still-molten magma.

Differentiation

This activity can be done as a demonstration if you prefer.

Wrap-up

Relate the sinking and floating objects to the differentiation of the Moon's magma ocean.

Differentiation

Purpose

To see how minerals separate from each other in a magma ocean.

Key Words

differentiation
density
magma ocean

Materials

pennies
sand
toothpicks
bowl
transparent container
water

Procedure

1. Mix the **pennies, sand, and toothpicks** in the **bowl**.

2. Fill the **container** with **water** to about 2 cm from the top.

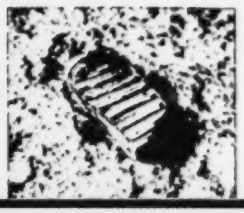
3. Predict what will happen when you drop a handful of the pennies-sand-toothpicks mixture into the water. Will they all sink to the bottom? Will some sink faster than others?

4. Now drop the mixture into the water. Wait until the objects stop moving and look at the deposits. What do you see?

5. Can you explain what causes the differences in the way the objects sink or float?

6. Suppose the mineral feldspar in the lunar magma ocean responded like the toothpicks in the water. What does this tell you about the formation of the original crust on the Moon?

7. What makes up the highlands of the Moon? Based on this experiment, does this make sense?



Impact Craters

Purpose

To determine the factors affecting the appearance of impact craters and ejecta.

Background [also see "Teacher's Guide" Pages 1, 2, photo on 8, 12, and photo on 13]

The circular features so obvious on the Moon's surface are **impact craters** formed when **impactors** smashed into the surface. The explosion and excavation of materials at the impacted site created piles of rock (called **ejecta**) around the circular hole as well as bright streaks of target material (called **rays**) thrown for great distances.

Two basic methods forming craters in nature are:
1) impact of a **projectile** on the surface and 2) collapse of the top of a **volcano** creating a crater termed *caldera*. By studying all types of craters on Earth and by creating impact craters in experimental laboratories geologists concluded that the Moon's craters are impact in origin.

The factors affecting the appearance of impact craters and ejecta are the size and velocity of the impactor, and the geology of the target surface.

By recording the number, size, and extent of erosion of craters, **lunar geologists** can determine the ages of different surface units on the Moon and can piece together the geologic history. This technique works because older surfaces are exposed to impacting **meteorites** for a longer period of time than are younger surfaces.

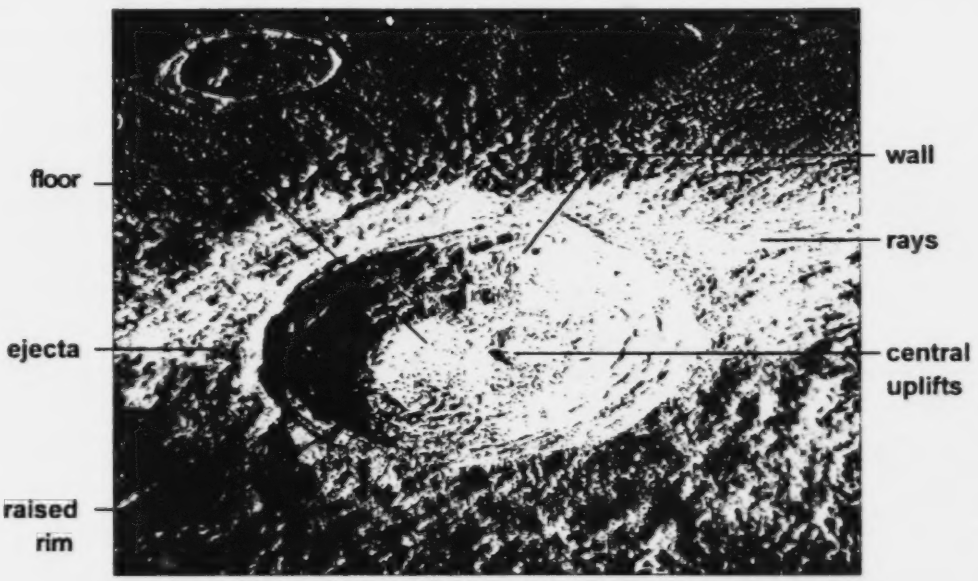
Impact craters are not unique to the Moon. They are found on all the terrestrial planets and on many moons of the outer planets.

On Earth, impact craters are not as easily recognized because of weathering and erosion. Famous impact craters on Earth are Meteor Crater in Arizona, U.S.A.; Manicouagan in Quebec, Canada; Sudbury in Ontario, Canada; Ries Crater in Germany, and Chicxulub on the Yucatan coast in Mexico. Chicxulub is considered by most scientists as the source crater of the catastrophe that led to the extinction of the dinosaurs at the end of the Cretaceous period. An interesting fact about the Chicxulub crater is that you cannot see it. Its circular structure is nearly a kilometer below the surface and was originally identified from magnetic and gravity data.

Impact Craters

Aristarchus

Typical characteristics of a lunar impact crater are labeled on this photograph of Aristarchus, 42 km in diameter, located West of Mare Imbrium.



raised rim - rock thrown out of the crater and deposited as a ring-shaped pile of debris at the crater's edge during the explosion and excavcation of an impact event.

floor - bowl shaped or flat, characteristically below surrounding ground level unless filled in with lava.

central uplifts - mountains formed because of the huge increase and rapid decrease in pressure during the impact event. They occur only in the center of craters that are larger than 40 km diameter. See Tycho crater for another example.

walls - characteristically steep and may have giant stairs called terraces.

ejecta - blanket of material surrounding the crater that was excavated during the impact event. Ejecta becomes thinner away from the crater.

rays - bright streaks starting from a crater and extending away for great distances. See Copernicus crater for another example.

Impact Craters

Preparation

Review and prepare materials listed on the student sheet.
In this activity, marbles or other spheres such as steel shot, ball bearings, golf, or wooden balls are used as impactors dropped from a series of heights onto a prepared "lunar surface." Using impactors of different mass dropped from the same height will allow students to study the relationship of mass of the impactor to crater size. Dropping impactors from different heights will allow students to study the realtionship of velocity of the impactor to crater size.

The following materials work well as a base for the "lunar surface" topped with a dusting of dry tempera paint or other material in a contrasting color:

all purpose flour	- Reusable in this activity and keeps well in a covered container.
baking soda	- It can be recycled for use in the lava layer activity or for many other science activities. Reusable in this activity, even if colored, by adding a clean layer of new white baking soda on top. Keeps indefinitely in a covered container. Baking soda mixed (1:1) with table salt also works.
corn meal	- Reusable in this activity but probably not recyclable. Keeps only in freezer in airtight container.
sand and corn starch	- Mixed (1:1), sand must be very dry. Keeps only in freezer in airtight container.
dry tempera paint or powdered drink mixes or glitter	- Sift on top; use a sieve, screen, or flour sifter. A contrasting color to the base materials gives striking results.

Pans should be plastic, aluminum, or cardboard. Do not use glass. They should be at least 7.5 cm deep. Basic 10"x12" aluminum pans or plastic tubs work fine, but the larger the better to avoid misses. Also, a larger pan may allow students to drop more marbles before having to resurface the target materials.

A reproducible student "Data Chart" is included; students will need a separate chart for each impactor used in the activity.

Impact Craters

In Class

1. Begin by looking at craters in photographs of the Moon and asking students their ideas of how craters formed.

2. During this activity, the flour, baking soda, or dry paint may fall onto the floor and the baking soda may even be disbursed into the air. Spread newspapers under the pan(s) to catch spills or consider doing the activity outside. Under supervision, students have successfully dropped marbles from second-story balconies. Resurface the pan before a high drop.

3. Have the students agree beforehand on the method they will use to "smooth" and resurface the material in the pan between impacts. The material need not be packed down. Shaking or tilting the pan back and forth produces a smooth surface. Then be sure to reapply a fresh dusting of dry tempera paint or other material. Remind students that better experimental control is achieved with consistent handling of the materials. For instance, cratering results may vary if the material is packed down for some trials and not for others.

4. Allow some practice time for dropping marbles and resurfacing the materials in the pan before actually recording data.

5. Because of the low velocity of the marbles compared with the velocity of real impactors, the experimental impact craters may not have raised rims. Central uplifts and terraced walls will be absent.

6. The higher the drop height, the greater the velocity of the marble, so a larger crater will be made and the ejecta will spread out farther.

7. If the impactor were dropped from 6 meters, then the crater would be larger. The students need to extrapolate the graph out far enough to read the predicted crater diameter.

Wrap-Up

Have the class compare and contrast their hypotheses on what things affect the appearance of craters and ejecta.

Impact Craters

Extensions

1. As a grand finale for your students, demonstrate a more forceful impact using a slingshot.

2. What would happen if you change the angle of impact? How could this be tested? Try it! Do the results support your hypothesis?

   If the angle of impact is changed, then the rays will be concentrated and longer in the direction of impact. A more horizontal impact angle produces a more skewed crater shape.

3. To focus attention on the rays produced during an impact, place a paper bulls-eye target with a central hole on top of a large, flour-filled pan. Students drop a marble through the hole to measure ray lengths and orientations.

4. Use plaster of Paris or wet sand instead of dry materials.

5. Videotape the activity.

6. Some people think the extinction of the dinosaurs was caused by massive global climate changes because of a meteorite impact on Earth. Summarize the exciting work that has been done at Chicxulub on the Yucatan coast of Mexico.

7. Some people think Earth was hit by an object the size of Mars that caused a large part of Earth to "splash" into space, forming the Moon. Do you agree or disagree? Explain your answer.

8. Physics students could calculate the velocities of the impactors from various heights. (Answers from heights of 30 cm, 60 cm, 90 cm, and 2 m should, of course, agree with the velocity values shown on the "Impact Craters - Data Chart".

Name: _____

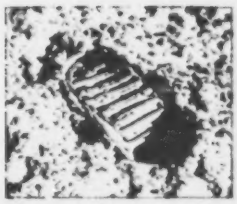
Date: _____

impactor # ____

____ gm

Impact Craters - Data Chart

		trial 1	trial 2	trial 3	total	average
drop height = 30 cm velocity = 242 cm/s	crater diameter					
	crater depth					
	average length of all rays					
drop height = 60 cm velocity = 343 cm/s	crater diameter					
	crater depth					
	average length of all rays					
drop height = 90 cm velocity = 420 cm/s	crater diameter					
	crater depth					
	average length of all rays					
drop height = 2 meters velocity = 626 cm/s	crater diameter					
	crater depth					
	average length of all rays					



Impact Craters

Purpose

To determine the factors affecting the appearance of impact craters and ejecta.

Key Words

impact

impactor

ejecta

Materials

1 pan

"lunar" surface material

tempera paint, dry

sieve or sifter

balance

3 impactors (marbles or other spheres)

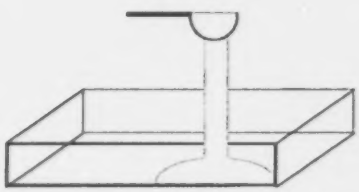
meter stick

ruler, plastic with middle depression

protractor

"Data Chart" for each impactor

graph paper



Procedure

Making an hypothesis

1. After looking at photographs of the Moon, how do you think the craters were formed?

_____

_____

_____

_____

_____

2. What do you think are factors that affect the appearance and size of craters and ejecta?

_____

_____

_____

_____

_____

Preparing a "lunar" test surface

1. Fill a **pan** with **surface material** to a depth of about 2.5 cm. Smooth the surface, then tap the pan to make the materials settle evenly.

2. Sprinkle a fine layer of **dry tempera paint** evenly and completely over the surface. Use a **sieve** or **sifter** for more uniform layering.

3. What does this "lunar" surface look like before testing?

_____

_____

_____

Cratering Process

1. Use the **balance** to measure the mass of each **impactor**. Record the mass on the "**Data Chart**" for this impactor.

2. Drop impactor #1 from a height of 30 cm onto the prepared surface.

3. **Measure** the diameter and depth of the resulting crater.

4. Note the presence of ejecta (rays). Count the rays, measure, and determine the average length of all the rays.

5. Record measurements and any other observations you have about the appearance of the crater on the Data Chart.
   Make three trials and compute the average values.

6. Repeat steps 2 through 5 for impactor #1, increasing the drop heights to 60 cm, 90 cm, and 2 meters. Complete the Data Chart for this impactor. Note that the higher the drop height, the faster the impactor hits the surface.

7. Now repeat steps 1 through 6 for two more impactors. Use a separate Data Chart for each impactor.

8. Graph your results.
   Graph #1: Average crater diameter vs. impactor height or velocity.
   Graph #2: Average ejecta (ray) length vs. impactor height or velocity.
   Note: on the graphs, use different symbols (e.g., dot, triangle, plus, etc.) for different impactors.

Results

1. Is your hypothesis about what affects the appearance and size of craters supported by test data? Explain why or why not.

2. What do the data reveal about the relationship between crater size and velocity of impactor?

3. What do the data reveal about the relationship between ejecta (ray) length and velocity of impactor?

4. If the impactor were dropped from 6 meters, would the crater be larger or smaller? How much larger or smaller? (Note: the velocity of the impactor would be 1,084 cm/s.) Explain your answer.

5. Based on the experimental data, describe the appearance of an impact crater.

6. The size of a crater made during an impact depends not only on the mass and velocity of the impactor, but also on the amount of kinetic energy possessed by the impacting object. Kinetic energy, energy in motion, is described as:

   $KE = 1/2(mv^2)$

   where, m = mass and v = velocity.
   During impact, the kinetic energy of an asteroid is transferred to the target surface, breaking up rock and moving the particles around.

7. How does the kinetic energy of an impacting object relate to crater diameter?

_____

_____

8. Looking at the results in your Data Tables, which is the most imporant factor controlling the kinetic energy of a projectile, its diameter, its mass, or its velocity?

_____

_____

9. Does this make sense? How do your results compare to the kinetic energy equation?

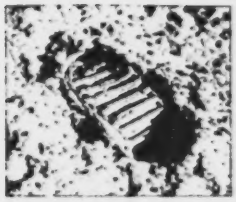
_____

_____

_____

_____

10. Try plotting crater diameter vs. kinetic energy as Graph #3. The product of mass (in gm) and velocity (in cm/s) squared is a new unit called "erg."



Clay Lava Flows

Purpose

To understand some of the geological processes and the structures that form as lava flows across planetary landscapes by using mud as an analog for lava.

Background [also see "Teacher's Guide" Pages 3, 4, 12, 13]

In this activity students will use mud to simulate surface **lava** flows. The experiment demonstrates many of the key features of **a'a** flows, though not of whole **pahoehoe** flow fields, which are fed by lava tubes.

Real a'a lava flows are complicated. They are characterized by a prominent lava **channel** confined between levees. Shear zones, places where one portion of the flow is moving faster than an adjacent portion, usually occur. Small flows of pahoehoe lava also become channelized, but on a much smaller scale than a'a flows.

As mud is poured onto an inclined surface, the first and foremost thing to do is to observe the formation of distinct features in the flow. **Levees** form on the outer part of the flow. These are not quite the same as levees on lava flows because the latter build up levees by overflowing the banks, but nevertheless, mud flows do form levees. Inside the levees the mud moves downhill. **Ridges** might develop in the flowing portions, analogous to large ridges in lava flows. The thickness of the flow varies with slope, time, position in the flow, and amount of mud poured. These variables can be tested by measuring width and thickness as functions of time, as described in the procedure.

Preparation

Review and prepare materials listed on the student sheet.
Mix clay and water in a bucket: 5 pounds of wet clay with 4 cups of water. To mix easily, break clay into half-inch pieces and allow to dry. The mixing process should be started at least 2 days before you intend to use the clay. Cover the bucket to keep the clay mixture from hardening.

The final clay-water mixture should be fairly uniform, with only a few lumps. Smooth the mixture with a wire whisk to the consistency of thick cream. If the mixture is too runny, then it will pour like water. If it is too thick, then it will mound up (though that is interesting and somewhat resembles some very viscous lava flows).

Plexiglas is an excellent surface to use for the experiment, though any nonporous surface will do fine, such as a wooden drawing board covered with plastic wrap. If the surface is too porous, then the mud loses moisture to it, changing flow characteristics.

Clay Lava Flows

Draw a grid with 10 cm spacing onto the Plexiglas using a permanent marker pen. Or draw a grid onto paper taped to the wooden board, then cover with plastic wrap.

In Class

Using a protractor and plumb line, the Plexiglas is propped up to an angle of 15° for the procedure, then to an angle of 25° for a repeat of the procedure.

Students should pour the clay slowly and at a constant rate down the inclined Plexiglas. The bucket should be held about 10 cm from the high end of the Plexiglas.

At each 10 cm mark, the students will:

1. record the time the flow front passes the mark,

2. measure the length of the flow,

3. measure the width of the flow,

4. measure the center depth of the flow.

"Data Tables" are provided for recording these values. Space is provided for sketches of the flow outline.

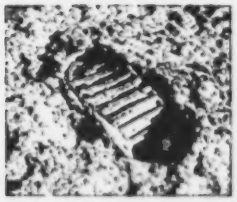
When the clay is flowing down the Plexiglas, look for areas near the edges where the flow rate is low or zero; these are the levees of the channel. The part in the middle that is moving faster is called the channel interior.

Wrap-up

How do the two flows compare?
Is the ratio of channel width to flow width the same?
Presumably the clay volumes were the same for both slopes, but the flow areas could be determined and multiplied by the average depths as an exercise just to check.

Extensions

1. Use a ruler with a grid to slice into the flow at each 10 cm mark to get cross sections.
2. Can you see the levee margins in the cross sections?
3. How do the cross sections change down the length of the flow?
4. Videotape the activity.
5. Use this clay in the "Impact Craters" activity on Page 61.



Clay Lava Flows

Purpose

To understand some of the geological processes and the structures that form as lava flows across planetary landscapes by using mud as an analog for lava.

Key Words

lava flows

channels and levees

pressure ridges

Materials

clay mixture

bucket, preferably with pouring spout

wire whisk

large spatula

Plexiglas or other nonporous surface (~1/2 by 1 meter, and preferably with a grid)

protractor with plumb line

stopwatch

"DataTables"

tape measure or ruler

Procedure

1. Stir your mixture of **clay** and **water** in the **bucket.** A few lumps are acceptable.

2. Prop up one end of the **Plexiglas** at an angle of about 15° (use the **protractor** and **plumb line** to determine the angle). A board under the Plexiglas helps prevent sagging.

3. Hold the bucket of clay mixture about 10 cm downslope from the high end of the Plexiglas. Keep the bucket about 10 cm above the Plexiglas surface. Pour the clay slowly. It is important to keep the pour rate as constant as possible. Start the **stopwatch** when the flow front passes the zero line.

4. Watch the flow as it goes downhill and spreads out, and record the time it reaches each 10 cm mark. How far behind the flow front does the distinct channel become apparent?

5. Record the time when you stopped pouring (the flow will continue to move). Fill in the "**Data Tables**."

6. Note the channel and levees as well as shear zones within the levees. Does the channel extend the entire length of the flow?

7. Using the **tape measure**, measure the length, width, and center depth of the flow and the channel width at each 10 cm mark. Fill in the "Data Tables."

8. Draw the outline of the flow using the grid as a guide.

9. Now prop the Plexiglas up higher to an angle of about 25° and repeat the procedure. The clay may flow off the end of the ramp onto the flat underlying surface. How do the structures in this flat part compare to those on the slope?

10. Repeat all the measurements and fill in the "Data Tables."

11. How do the two experimental flows compare? Is the ratio of channel width to flow width the same?

Clay Lava Flows

Data Tables

Angle	Time at 0	10	20	30	40	50	60	70	80	90	Time stopped pouring
15°											
25°											

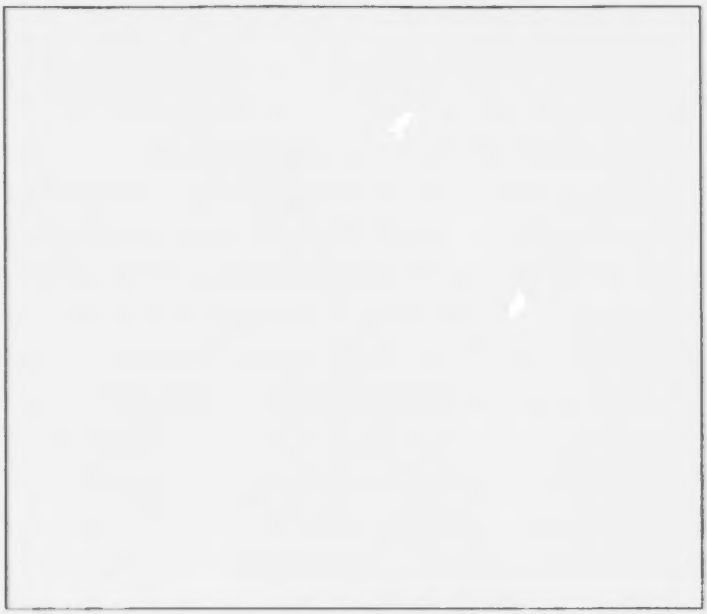
Angle	Width at 0	10	20	30	40	50	60	70	80	90	Total length
15°											
25°											

Angle	Center-line depth at 0	10	20	30	40	50	60	70	80	90
15°										
25°										

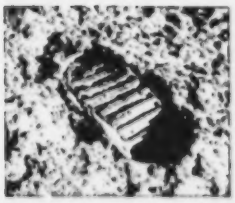
Angle	Channel width at 0	10	20	30	40	50	60	70	80	90
15°										
25°										

Clay Lava Flows

Sketch of flow at 15°



Sketch of flow at 25°



Lava Layering

Purpose

To learn about the stratigraphy of lava flows produced by multiple eruptions.

Background [also see "Teacher's Guide" Pages 3, 4, 12, 13]

Dark, flat **maria** (layers of **basaltic lava** flows) cover about 16 percent of the Moon's total surface. They are easily seen on a full Moon with the naked eye on clear nights from most backyards. The maria, quite similar to Earth's basalts, generally flowed long distances utlimately flooding low-lying areas such as **impact** basins. Yet, the **eruption sources** for most of the lunar lava flows are difficult to identify. The difficulty in finding source areas results from burial by younger flows and/or erosion from meteoritic bombardment.

Generally, the overall slope of the surface, local topographic relief (small cliffs and depressions), and eruption direction influence the path of lava flows. Detailed maps of the **geology** of the Moon from photographs reveal areas of complicated lava layering. The study of rock layering is called **stratigraphy**.

On the Moon, older flows become covered by younger flows and/or become more pocked with impact craters.

On Earth, older lava flows tend to be more weathered (broken) and may have more vegetation than younger flows. Field geologists use differences in roughness, color, and chemistry to further differentiate between lava flows. They also follow the flow margins, **channels**, and **levees** to try to trace lava flows back to the source area.

The focus of this activity is on the patterns of lava flows produced by multiple eruptions. We use a short cup to hold the baking soda because we are looking at the flows and not at constructing a volcano model. Volcanoes, like those so familiar to us on Earth and Mars, are not present on the Moon. Three well-known areas on the Moon interpreted as important volcanic complexes are: Aristarchus plateau, and the Marius Hills and Rumker Hills (both located in Oceanus Procellarum). These areas are characterized by sinuous rilles (interpreted as former lava channels and/or collapsed lava tubes) and numerous domes.

Lava Layering

Preparation

Baking soda-vinegar solutions and playdough are used to model the basaltic lavas. Different colors identify different eruption events; this activity calls for 4 colors. Students will be asked to observe where the flows traveled and to interpret the stratigraphy. Cover the work area and be prepared for spills.

Play Dough (stove-top recipe)

-best texture and lasts for months when refrigerated in an air tight container.

2 cups flour	1/3 cup oil, scant
1 cup salt	2 cups cold water
4 teaspoons cream of tarter	food colorings (20 drops more or less)

Make this large batch one color or divide ingredients in half to make 2 colors. You will need 4 colors total. Combine ingredients and cook mixture in a large sauce pan, stirring constantly, until the dough forms a ball. Turn dough cut onto a floured surface to cool. Then kneed until smooth and elastic. Cool completely; refrigerate in air tight containers.

Play Dough (no-cooking recipe)

2 cups flour	2 Tablespoons oil
1 cup salt	1 cup cold water
6 teaspoons alum or cream of tartar	food colorings (as above)

Make this large batch one color or divide ingredients in half to make 2 colors. You will need 4 colors total. Mix ingredients and kneed until smooth and elastic. Store in air tight containers.

In Class

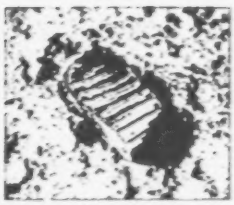
This activity can be done individually or in cooperative teams.
Making a vertical cut through the flows reveals, quite dramatically, the stratigraphy of the section.

Wrap-up

Have students compare their layered lava patterns with their classmates' patterns. Did they recognize individual flows by color and outline? Point out how the oldest flow is on the bottom of the stack and the youngest flow is on top.

Extensions

Groups can trade landscapes before answering the questions. Clear, plastic drinking straws can be pushed down into the landscapes to extract "drill" samples of the layers.



Lava Layering

Purpose

To learn about the stratigraphy of lava flows produced by multiple eruptions.

Key Words

eruption

source

stratigraphy

Materials

paper cups, 4 oz. size, some cut down to a height of 2.5 cm

cafeteria tray or cookie sheet, 1 for each eruption source

tape

tablespoon

baking soda

measuring cup

vinegar

food coloring, 4 colors; for example, red, yellow, blue, green

playdough or clay in the same 4 colors as the food coloring

plastic knife, string, or dental floss: to slice through the layers of playdough

Procedure

1. Take one **paper cup** that has been cut to a height of 2.5 cm and secure it onto the **tray**. (You may use a small loop of **tape** on the outside bottom of the cup.) This short cup is your eruption source and the tray is the original land surface.

2. Place one **Tablespoon of baking soda** in this cup.

3. Fill 4 tall paper cups each with **1/8 cup of vinegar.**

4. To each paper cup of vinegar add 3 drops of **food coloring;** make each cup a different color. Set them aside.

5. Set aside small balls of **playdough**, one of each color.

6. You are now ready to create an eruption. Pour red-colored vinegar into your source cup and watch the eruption of "lava."

7. As best you can, use red playdough to cover the areas where red "lava" flowed.

8. Repeat steps 6 and 7 for each color of vinegar and playdough. You may add fresh baking soda to the source cup or spoon out excess vinegar from the source cup as needed.

Lava Layering

Results

1. After your four eruptions, can you still see the original land surface (tray)? Where?

2. Describe what you see and include observations of flows covering or overlapping other flows. Use the left page margin to make a sketch.

3. Where is the oldest flow?

4. Where is the youngest flow?

5. Did the flows always follow the same path? (be specific)

6. What do you think influences the path direction of lava flows?

7. If you had not watched the eruptions, how would you know that there are many different layers of lava? Give at least 2 reasons:

Lava Layering

8. Which of the reasons listed in answer 7 could be used to identify real lava layers on Earth?

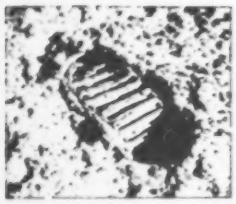
9. What are other ways to distinguish between older and younger layered lava flows on Earth?

10. Which of the reasons listed in answer 9 could be used to identify lava layers on the Moon?

11. What are other ways to distinguish between older and younger layered lava flows on the Moon?

12. Make a vertical cut through an area of overlapping playdough "lava" layers. Draw what you see in the vertical section. Color your sketch and add these labels:
oldest flow, youngest flow.

Vertical section through the flows



Lunar Landing Sites

Purpose

To design a spacecraft for travel to and from the Moon and choose an interesting lunar landing site.

Background [also see "Teacher's Guide" Pages 2-5]

The previous Unit 2 activities introduce the Moon's rocks, surface features, and the geologic processes that formed them. With this background, students are given the challenge to plan a mission to the Moon. In this activity, teams of students design a spacecraft, choose a suitable lunar landing site, and present their ideas before the entire class. Final presentations should include speeches and visual aides such as maps, diagrams, and 3-dimensional models.

Preparation

Review and prepare materials listed on the student sheet. Schedule library time as needed.

In Class

Lead a discussion on what the students need to know about the Moon in general and about potential landing sites *before* landing. A review of the Apollo sites may help initiate a discussion.

After presenting the scenario and tasks to the class, form cooperative teams of 3-4 students. Each student will have assigned duties, as described on the reproducible "Team Duty Sheet."

For the presentations, either 3-D models or poster-size diagrams can be made, depending on resources and time. Any one or all team members may participate in the presentations.

Scenario: NASA has given you the assignment to develop a spacecraft that can fly people safely to the Moon, land, and return to Earth. You must select a safe yet interesting lunar landing site for the spacecraft.

- Size, mass, propulsion, number of crew, life support systems, and methods of takeoff and landing should be considered for the spacecraft. Geology, terrain, safety, and length of stay should be considered for the lunar landing site.

Lunar Landing Sites

Wrap-up

1. How do the sites chosen by the class compare in location and geologic diversity with the Apollo sites?

2. What made some spacecraft designs and landing sites, in this activity, more risky than others?

3. Are these lunar landing sites good for short-term visits only, or could the sites be appropriate for lunar base development?
See the "Lunar Land Use" activity on Page 101.

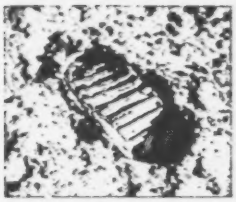
Extensions

Spacecraft design could be conducted as a spin-off of the "egg drop" contest. Each spacecraft is constructed to hold and protect one raw egg. The egg must remain unbroken after landing from a high drop (perhaps a second-story balcony).

Some students may enjoy learning more details of Apollo site selections.
A detailed discussion of how the sites were chosen is given in *To A Rocky Moon* by Don E. Wilhelms, Univ. of Arizona Press, 1993.

Use these lunar landing sites in the "Lunar Roving Vehicle" activity on Page 87, stipulating that the vehicle must be able to work on the terrains.

Use these lunar sites in the "Lunar Land Use" activity on Page 101.



Lunar Landing Sites

Purpose

To design a spacecraft for travel to and from the Moon and chose an interesting lunar landing site.

Materials

Moon maps

Apollo landing sites map

"Moon ABCs Fact Sheet"

Moon slides

background literature, such as the "Teacher's Guide"

"Team Duty Sheet"

art and construction supplies

Scenario

NASA has given you the assignment to develop a spacecraft that can fly people safely to the Moon, land, and return to Earth. You must also select a safe yet interesting lunar landing site for the spacecraft.

Size, weight, propulsion, number of crew, life support systems, and methods of takeoff and landing should be considered for the spacecraft. Geology, terrain, safety, and length of stay should be considered for the lunar landing site.

Procedure

1. Read the "Team Duty Sheet" given to your team.

2. Design a spacecraft with all necessary sytems that can go to the Moon, land, and return to Earth. Build a model or draw a detailed diagram of the design.

3. Study maps of the lunar sufrace and use your knowledge of the Moon to determine a safe yet interesting lunar landing site.

4. Make a presentation to the class:
   (a) about your spacecraft and its special features using diagrams and/or a model,
   (b) describing, locating, and justifing the landing site.

Names: _____

Date: _____

Lunar Landing Sites

TEAM DUTY SHEET

Your team must design a spacecraft and determine a safe yet interesting place to land on the Moon.

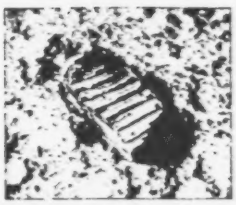
Everyone on your team should be assigned one or more of the following duties:

Chief Engineer : oversees the entire project, helps to design spacecraft, makes critical decisions for the team.

Scientist : designs spacecraft, oversees the construction of the model or diagrams of the spacecraft.

Lunar Geologist : studies maps of the Moon and oversees the selection of a safe yet interesting place to land the spacecraft.

Public Relations Manager : helps scientist and geologist, oversees the presentation of the spacecraft and landing site before the class.



Lunar Roving Vehicle

Purpose

To construct a model of a lunar roving vehicle.

Background

The **Apollo lunar roving vehicle** was a battery-powered space buggy. The **astronauts** on Apollo 15, 16, and 17 used it to explore their landing sites and to travel greater distances than astronauts on earlier missions. The lunar rover neatly folded up inside the lunar lander during trips to the Moon. Once on the Moon's surface, it unfolded with the help of springs. The lunar rover carried two astronauts and was manually driven. It was designed to climb steep slopes, to go over **rocks**, and to move easily over the Moon's **regolith**. It was able to carry more than twice its own weight in passengers, scientific instruments, rocks, and regolith samples. The wheels on the rover were made of wire mesh (piano wire) with titanium cleats for treads. Engineers did not use solid or air-filled rubber tires because they would have been much heavier than were the wire mesh wheels. The Apollo **spacecraft** had a fixed amount of mass (payload) it could deliver to the surface, including the rover, rover batteries, scientific instruments, sample collection devices, etc. Hence, the wire-mesh wheels were important to the overall payload mass. This rover was not designed for prolonged use, and it is uncertain if future lunar explorers would use similar designs and materials for their vehicles, use new, more durable components, or turn to **robotic** rovers.

If students are interested in constructing models that actually move, then refer to Page 38 for more information on rocket and model building.

Preparation

Review and prepare materials listed on the student sheet. While commercial building sets are very popular, models can be built with more simple and recyclable materials such as cardboard boxes, tubes, cans, straws, construction paper, string, tape, pins, styrofoam trays, thread spools, balloons, rubber bands, and mouse traps (for propulsion).

In Class / Wrap Up

After construction, students should name their vehicles and write a description of the capabilities and special features.

Lunar Roving Vehicle

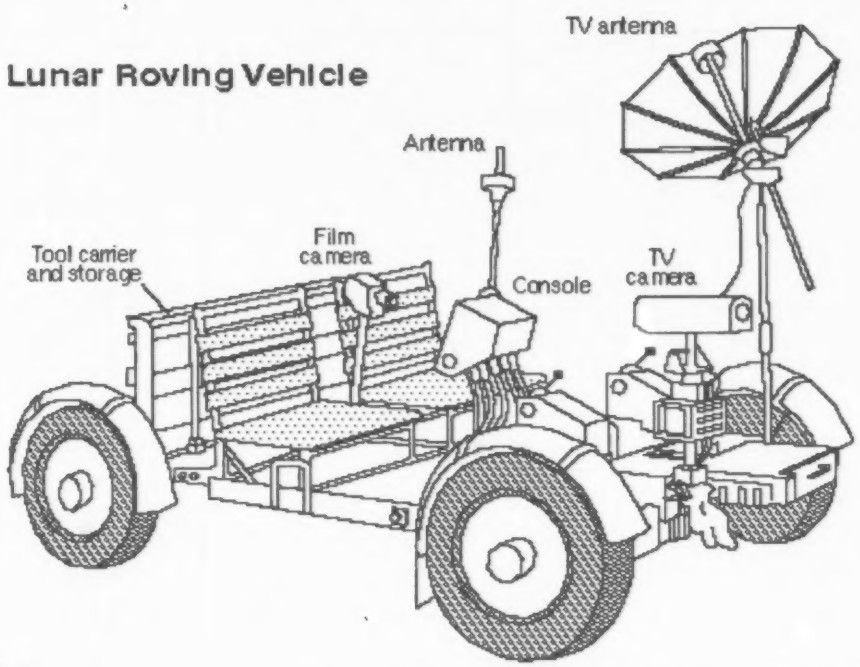
Extensions

Hold competitions between student vehicles with these criteria for judging:

1. Can the vehicle actually move -- by gravity; by some kind of propulsion system?
2. Can the vehicle go over different surfaces -- smooth, flat, bumpy, or inclined?
3. Is the vehicle sturdy?
4. Can the vehicle carry a heavy load? Have the students decide the weight of the load.
5. Could the vehicle withstand meteoritic bombardment?
6. Would the vehicle work on the Moon?

Discuss the pros and cons of manually driven vehicles versus remote-controlled robotic rovers on the Moon.

Diagram of the vehicle used by Apollo astronauts.



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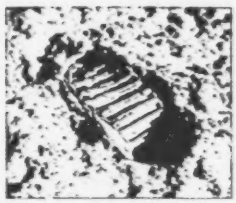


Lunar Roving Vehicle

Purpose

To construct a model of a lunar roving vehicle.

Key Words

antenna

console

tool carrier and storage

robot

Materials

diagram of Apollo lunar roving vehicle

"Moon ABCs Fact Sheet"

construction materials such as cardboard boxes, tubes, cans, straws, construction paper, string, tape, pins, styrofoam trays, thread spools, balloons, rubber bands, mouse traps, etc.

tape measures

stop watches

Procedure

1. Describe the similarities and differences between the Apollo lunar roving vehicle and a typical family vehicle.

2. What was special about the rover's wheels? Why weren't they made of rubber and filled with air?

3. Review the "**Moon ABCs Fact Sheet.**" Design a new lunar roving vehicle. Important design issues include size, weight, power supply, number of passengers, controls, scientific instruments, tools, and storage compartments. Use the space provided on the next page to draw a picture of your design. Label the parts.

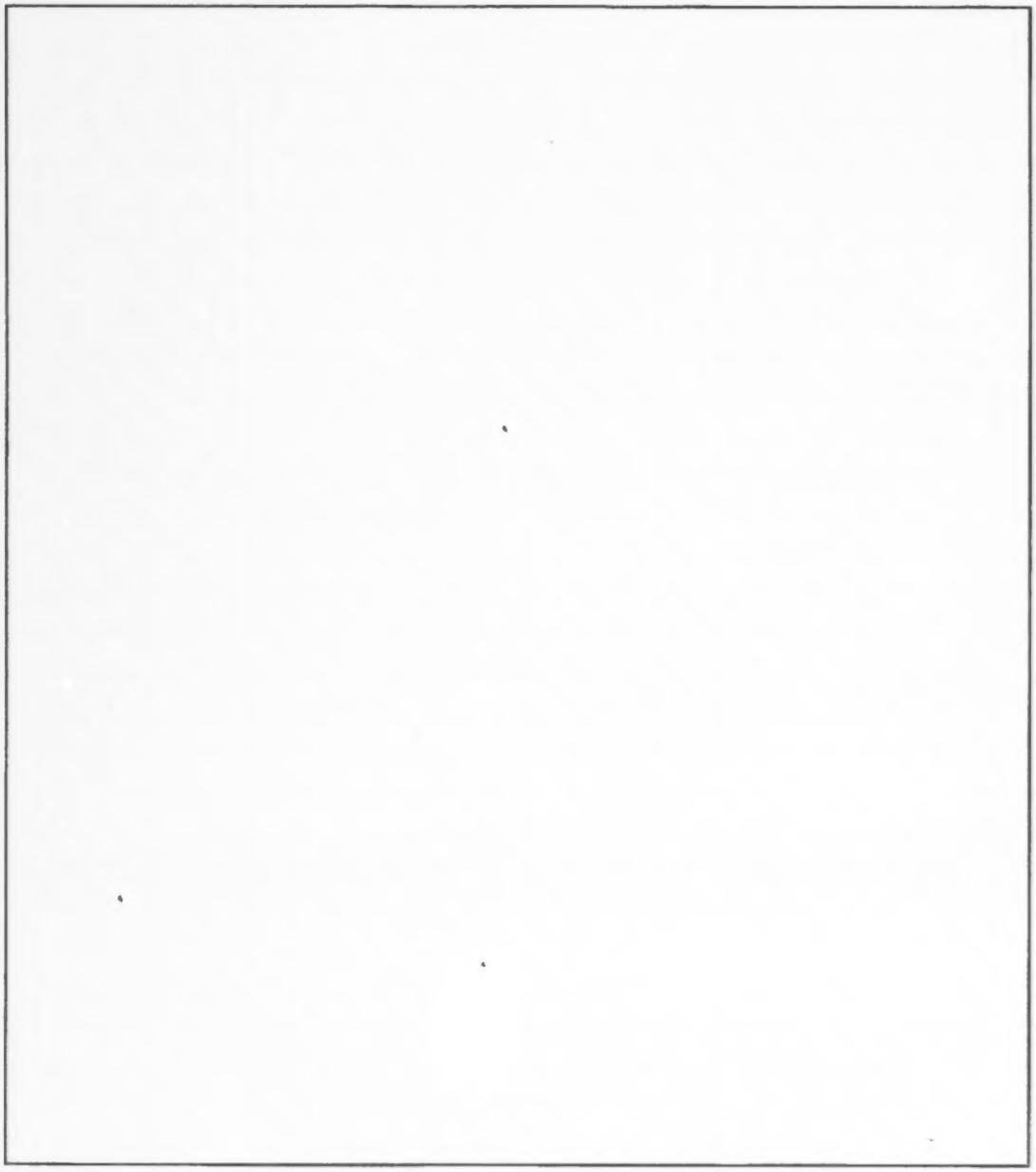
4. Construct a model of the lunar rover based on your design.

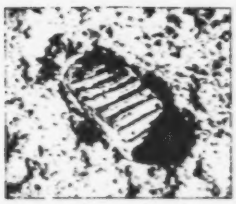
5. Give a name to the vehicle.

6. Write a descriptive essay about the special features and capabilitites of the vehicle and how you solved the design issues raised in Question 3.

Lunar Roving Vehicle

Sketch of my model





Moon Anomalies

Purpose

To investigate and try to explain various lunar anomalies.

Background [also see "Teacher's Guide" Pages 4, 10]

In this activity teams of students present hypotheses that attempt to resolve four anomalies of the Moon. They will be expected to prepare written and oral presentations for the entire class. Using a forum format, students will debate the merits of each hypothesis, with no right or wrong answers.

The four anomalies are:
"Quakes or No Quakes, that is the Question"
"Where Have All the Volcanoes Gone?"
"Maria, Maria, Where For Art Thou?"
"Magnetic Field Forever?"

Some of these anomalies are more complicated than others. The class need not discuss all the anomalies; the most straightforward are Quakes and Missing Volcanoes.

Preparation

Review and prepare materials listed on the student sheets.
Schedule library time, if needed.

Some possible solutions to the anomalies

Quakes or No Quakes, that is the Question

The number and strength (magnitude) of **moonquakes** is much less than the number and magnitude of **earthquakes**. The probable cause of this difference is the Moon's smaller size and cooler interior. Earth is hot and active, manifested most dramatically in **plate tectonics**. Tectonic plate motions in Earth are driven by convection in the **mantle**—the solid mantle actually moves at rates of a few centimeters a year. The Moon's mantle, too cool to move easily, has no convection and no active tectonic plate motions. Fewer movements inside the Moon mean fewer quakes. The few moonquakes that do occur are driven primarily by gravitational tugs by Earth and Sun (tides in the solid Moon).

Moon Anomalies

Where Have All the Volcanoes Gone?

The Moon has lots of **lava** flows, but no (or at least few) **volcanoes**. The clue to solving this dilemma lies in understanding why volcanoes form on Earth, Mars, and Venus. In fact, those bodies also have large expanses of lava flows that are not associated with volcanoes. For example, vast deposits of lavas occur in Oregon, Washington, and Idaho. These are called the Columbia River Basalts. They **erupted** from long cracks called **fissures** and flowed across the surface. The path the magma took was far different from that in other places. The magma never concentrated to narrow conduits that were fed periodically over a long time to form a high mountain over the site.

The transport of magma for the Columbia River basalts was controlled by the stress environment of the region. Long fissures developed which provided the magma with pathways to the surface. On the Moon, plenty of fractures occur around the rings of the multi-ringed basins. These fractures undoubtedly extend far into the Moon, and may have provided easy access to the surface for magma, and at the same time did not allow the magma paths to concentrate in one small area. Result: no large volcanoes formed. The idea that some did form but were destroyed by impacts is always a possibility on the Moon, but lots of volcano-sized mountains on basin rings survived, so one would expect volcanoes to do so, too.

Maria, Maria, Where For Art Thou?

Almost all of the lunar maria decorate the Earth-facing side of the Moon. Only a few add contrast to the **farside**. See the first two photographs in the "Teacher's Guide" on Page 1. The most likely cause of this asymmetry is the variation in thickness of the Moon's **crust**. The crust is lower in density than the mare-basalt magmas that must pass through it to erupt onto the surface. This, in turn, requires that the magmas have a sufficient driving pressure to migrate through the crust. Scientists think that magmas on the Moon tend to stall and collect at the base of the crust. They stay there until the pressure is enough to begin to form fissures for the magmas to travel through. On the nearside, the crust is about 70 kilometers thick. Many of the mare-basalt magmas were able to reach the surface once the pressure was large enough to form cracks. However, on the farside, the crust is twice as thick, so very few magmas could reach the surface. Most stalled on their way through it.

Magnetic Field Forever?

The lunar **magnetic field** is one of the least understood properties about the Moon. It is about 10,000 times weaker than Earth's magnetic field. The Moon had a weak field in the past, but none is being generated at the present time.

Moon Anomalies

The most likely reason for the decline in field strength is that the Moon's tiny metallic **core** (no larger than 400 kilometers in radius) did generate a field the way Earth's core does, but the field-generating engine kept losing power. Earth's field is generated by convective motions inside the liquid portion of the core: hotter iron rises, cooler iron sinks, and the differential motions create a magnetic field. On the Moon, the whole body cooled much faster than Earth (because the Moon is smaller), so the core also cooled, and probably solidified. Motions fast enough to generate a magnetic field do not occur today inside the Moon's core.

In Class

Divide the class into cooperative teams of 4-5 students. Encourage each team to generate a team name and logo. Give each team a "Task Sheet" describing their duties. Each team then develops a hypothesis that reconciles the dilemma given them. They must work together to produce a written report describing their anomaly, hypothesis, and supporting evidence. You may want to copy and distribute all the final reports so each team has a complete set.

When the teams make their oral presentations to the class they must use visual aid materials, such as maps, posters, charts, slides, laserdiscs, etc. After each presentation, other teams may challenge the presenters with questions or arguments.

Wrap-up

After all teams have presented, lead a discussion to summarize what has been learned.

Extension

You may wish to discuss another mysterious aspect of the Moon's magnetic field: the presence of several small areas (30-60 kilometers across) that have exceptionally large surface magnetism, about 10 times the normal Moon magnetic field. These are associated with bright swirly deposits. Possible origins include impact of a comet that is highly magnetized or magnetization of a comet during impact. In either case, the magnetism is transferred to the ejecta deposits at the site of impact. Another suggestion is that the field results from giant, basin-forming impacts. It turns out that most, but not all, magnetic swirl deposits are on the exact opposite side of the Moon from a large basin (i.e., antipodal to the site of impact). The idea is that seismic waves generated by the large impact interact vigorously when they meet half way around the Moon. Somehow these interactions reinforce existing magnetic fields to create the anomaly. The whitish swirls, by the way, may form because the solar wind (mostly hydrogen nuclei) is deflected by the strong magnetic field. Thus, no hydrogen gets implanted into the regolith, and subsequent micrometeorite bombardment does not cause formation of dark agglutinates. Instead of being dark glass, the agglutinates are colorless or nearly so.

Names: _____

Date: _____

Moon Anomalies

Task Sheet

Everyone on your team should be assigned one or more of the following tasks:

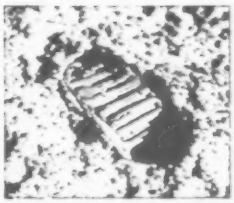
Chief Stratigist : oversees the entire project, works closely with all members, makes critical decisions.

Material Person : collects, cares for, and returns all materials needed for the activity.

Media Consultant : oversees development of all the visual aid materials that your team will use during the presentation, such as maps, posters, models, etc. Also coordinates the use of slides, photographs, laserdisc, computer, etc.

Administrator : keeps notes, assists media consultant, and prepares final written report.

The oral presentation may be made by any one or all team members.



Quakes or No Quakes, that is the Question

Purpose

To investigate and try to explain why the Moon has fewer moonquakes than Earth has earthquakes.

Key Words

earthquake

moonquake

Materials

maps of the Moon

background information on the Moon

"Moon ABCs Fact Sheet"

"Task Sheet"

art supplies

Background

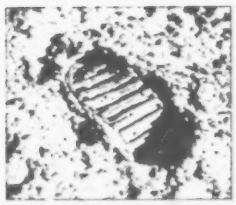
The Moon is safer than San Francisco—at least from earthquake damage. Each year Earth has more than 10,000 earthquakes of magnitude 4 or greater. In contrast, the Moon has less than 500, and most of these are smaller than magnitude 2.5. The largest moonquake recorded during the eight years that the Apollo seismic instrument operated on the Moon was slightly less than magnitude 5. On Earth, the largest quakes reach magnitude 8, or even 9. Finally, the total amount of energy released by moonquakes is the same as released by three 100-watt light bulbs. Earthquakes release the equivalent of 300,000,000 100-watt light bulbs.

Dilemma

Why does the Moon have fewer quakes than Earth? Is it because people live on Earth? Because the Moon is smaller? Because Earth has moving tectonic plates? Because the Moon has craters?

Task

Develop an hypothesis that explains why the Moon has fewer quakes than Earth.



Where Have All the Volcanoes Gone?

Purpose

To investigate and try to explain the absence of volcanoes on the Moon.

Key Words

volcano

lava flows

maria

Materials

maps of the Moon

background information on the Moon

"Moon ABCs Fact Sheet"

"Task Sheet"

art supplies

Background

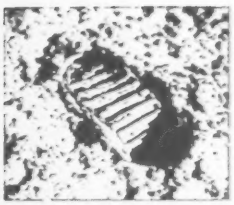
The dark areas of the Moon's surface, called the lunar maria, are composed of solidified lava flows. Scientists know this from photographs that show the margins of individual lava flows and from examination of rocks returned from the maria. The lava plains cover 16% of the lunar surface and are up to about 2 kilometers thick. This is a substantial amount of lava. Scientists estimate that a total of 10 million cubic kilometers of lava erupted during a period of about a billion years to fill the mare basins. This is a lot of lava! -- enough to fill 10 billion football stadiums! Most of the maria occur inside the huge circular impact craters called multi-ringed basins. The formation of these immense craters did not cause the formation of the lava that made the maria, but the basins did provide low areas into which the liquid lava flowed.

Dilemma

Ten million cubic kilometers of lava flowed across the Moon's surface, yet there are no obvious source volcanoes. There are no mountains that rise dramatically as they do in Hawai'i or the Cascades of the Pacific Northwest. If there are no volcanoes on the Moon, then what is the source of the lava? Were the volcanoes destroyed? Did the lava erupt in some other way? What other ways could lava erupt?

Task

Develop an hypothesis that resolves the missing volcanoes dilemma, without rejecting the idea that the maria are composed of solidified lava flows.



Maria, Maria, Where For Art Thou?

Purpose

To investigate and try to explain why the farside has fewer maria than the nearside of the Moon.

Key Words

maria

crust

lava flows

Materials

maps of the Moon

background information on the Moon

"Moon ABCs Fact Sheet"

"Task Sheet"

art supplies

Background

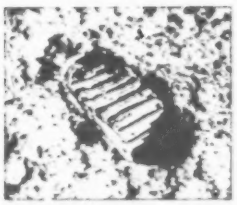
About 16% of the Earth-facing side of the Moon is covered with dark maria. But less than 1% of the farside is covered with maria. Scientists think that the magmas were formed inside the Moon by melting of the Moon's mantle, and that these magmas then moved to the surface. They probably moved in long cracks. Good evidence suggests that the crust on the farside is about two times thicker than on the nearside.

Dilemma

Assuming magma was generated throughout the Moon's mantle, why are almost all the maria on the nearside of the Moon? Did they get covered up by other rocks on the farside? Did Earth's gravity help them get out onto the nearside? Was it too hard to travel through the thick, farside crust?

Task

Develop an hypothesis that resolves the maria-are-more-abundant-on-the-nearside dilemma.



Magnetic Field Forever?

Purpose

To investigate and try to explain why the Moon has a weaker magnetic field than does Earth.

Key Words

magnetic field

core

Materials

background information on the Moon

"Moon ABCs Fact Sheet"

"Task Sheet"

art supplies

Background

The Moon has a much weaker magnetic field than does Earth. However, the field was stronger in the past, as shown by study of the magnetic properties of lunar rocks. Earth's magnetic field is formed by motions inside its iron core. The Moon also has a core, but it is much smaller than Earth's core. The Moon's core is no larger than 400 kilometers in radius, and may be as small as 100 kilometers. In contrast, Earth's core is 2900 kilometers in radius.

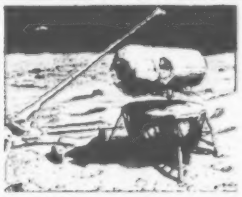
Dilemma

The Moon had a stronger magnetic field in the past (billions of years ago), but it is weak now, much weaker than Earth's magnetic field. Why is it so much weaker than Earth's? Why was it stronger in the past?

Task

Develop an hypothesis that explains why the Moon has a weaker magnetic field than does Earth, and why the Moon's field was stronger in the past.

Unit 3



The Future

Lunar Land Use
Life Support Systems
Lunar Biosphere

The activities in this unit spark interest in responsible land use and sustainable human settlements on the Moon. Each activity uses and reinforces all the knowledge the students have been gaining about the Moon and Earth from Units 1 and 2. These activities require teamwork, research, and development of model systems.

The maps produced by Clementine and Lunar Prospector will be useful for planning other types of missions, such as automated sample returns, robotic rovers, or human exploration. The chemical data allow sensible choices of landing sites to be made to optimize the scientific or industrial return from future missions.

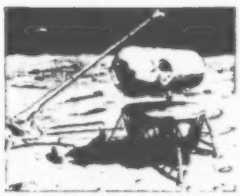
A Resource Section for Unit 3 is on Page 100.

Unit 3

Resource Section

This list presents possible independent and commercial sources of items to complement the activities in Unit 3. The sources are offered without recommendation or endorsement by NASA. Inquiries should be made directly to the appropriate source to determine availability, cost, and ordering information before sending money. Contact your NASA Educator Resource Center (see Page 146) for more resources available directly from the National Aeronautics and Space Administration.

Bottle Biology, by the Bottle Biology Project, 1993, Kendall/Hunt Pub. Co.,127 p. An idea book for exploring the world through plastic bottles and other recyclable materials.
Dept. of Plant Pathology, College of Agricultural and Life Sciences, University of Wisconsin-Madison
1630 Linden Dr.
Madison, WI 53706
608-263-5645



Lunar Land Use

Purpose

To design a development on the Moon that is suitable, feasible, and beneficial.

Background [also see "Teacher's Guide" Pages 14, 15]

In this activity teams of students will present proposals for developments on the Moon in a competition for approval from a student-staffed Lunar Council. This activity commonly runs 8 class days.

Preparation

Review and prepare materials listed on the student sheet.

In Class

Present the scenario and divide the class into cooperative teams of 4-5 students. Each team will represent a development corporation that will make a proposal before the Lunar Council.

You will also need 3 other students to comprise this Lunar Council.

Each student will have assigned duties, as described on the reproducible "Information Sheets."

Scenario: Travel to and from the Moon has become economical. As a result, the Moon's development has become inevitable and several corporations have already approached the United Nations about the prospects of developing lunar projects. In response, the U.N. has set up a Lunar Council to consider the feasibility and suitability of each proposal.

You may want to brainstorm ideas with the class for projects on the Moon; they may include mining communities, scientific bases, telescopic outposts, government headquarters, recreational bases, tourist sites, etc. You could assign a different idea to each team.

Distribute an "Information Sheet" to each development team. Give them 3-5 days to decide what their developments will be and to design their maps, models, diagrams, etc. Not only must they present their plan before the Lunar Council, but they must convince the council of the plan's worthiness. Lobbying efforts and advertising are all part of the game as long as they are fair.

Lunar Land Use

Distribute "Information Sheets" to the Lunar Council. Their task is to organize and run a hearing regarding development on the Moon. The ultimate approval for development is in their hands.

When most of the teams have finished, let the Lunar Council set the hearing date and let the proceedings begin.

Wrap-up

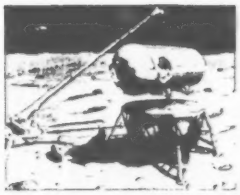
Once a decision is rendered, distribute the "Wrap-up Questions" or discuss them as a class.

Extensions

1. Have the students bid for project sites or use the landing sites chosen in the "Lunar Landing Sites" activity on Page 83.

2. Hold a classroom debate on "Who owns the Moon?"

3. Have the students compare Antarctica to the Moon.



Lunar Land Use

Purpose

To design a development on the Moon that is suitable, feasible, and beneficial.

Key Words

development

feasible

beneficial

Materials

maps of the Moon

"Moon ABCs Fact Sheet"

backgound information on the Moon

"Information Sheets"

art and construction supplies

Scenario

Travel to and from the Moon has become economical; as a result, the Moon's development has become inevitable. Several corporations have already approached the United Nations with lunar proposals.

In response, the U.N. has set up a Lunar Council to look at the suitability and feasibility of each proposal.

If your team is one of the development corporations, then your job is to decide what you want to build on the Moon and where to put it, to make the maps, diagrams, and/or 3-dimensional models of your project, and to convince the Lunar Council that your project is worthy of approval.

If you are a Lunar Council member, then the development of the Moon rests on your decisions.

Lunar Land Use

Procedure

1. Read the "Information Sheet" given to your group, either a development team or the Lunar Council, and divide the duties.

2. Each development team must execute a development plan and design all necessary maps, diagrams, and/or 3-dimensional models.

3. Each development team must follow the guidelines set forth by the Lunar Council.

4. Each development team must present a plan for approval.

5. The Lunar Council reviews all the plans and decides which, if any, will be accepted.

Names: _____

Date: _____

Lunar Land Use

Team Member Information Sheet

Tasks

Your team must decide what you want to build and where you want to build it. Everyone on your team should be assigned one or more of the following tasks:

Chief Engineer : oversees the entire project, makes critical decisions, assists in the design of the project.

Lunar Geologist : studies the Lunar Sample Disk and researches the minerals that may exist on the Moon for mining and/or for use as building materials. Chooses a suitable site for the project.

Media Consultant : oversees development of all the visual aid materials your team uses to present your proposal, such as maps, posters, and models. Also coordinates the use of slides, photographs, laser disc, etc. used to enhance your presentation.

Administrator : keeps notes, assists media consultant, works closely with the reporter to develop the speech to be given to the Lunar Council and types this final written proposal.

Reporter : works closely with all members to write the speech that will be given before the Lunar Council. The actual presentation may be made by any one or all team members.

Remember, you will have to "sell" your ideas before the Lunar Council. You need a well-planned project. Focus on how your project will be used, how it will benefit people, how it is environmentally friendly, etc.

Anything goes as long as it is actually possible. For example, if you are asked where the money is coming from to back your project you could say you have investors who will recover their money plus interest when the project makes money. You cannot have stories like "a limousine drove by and out popped a suitcase full of money." Have fun!

Names: _____

Date: _____

Lunar Land Use

Lunar Council Information Sheet

Tasks

You are representatives of the United Nations and have been chosen to decide how the Moon will be developed. Your job is to organize and run a hearing where various teams will make proposals to you concerning the development of the Moon. Your ultimate task will be to choose one or more of the proposals brought before you. If you wish, you can choose none of the proposals or allow certain ones with restrictions or improvements.

Everyone on the Council should hold one of the following positions:

Chairperson : runs the hearing by calling on the teams for their presentations, calls on Council members and the public to ask questions, makes critical decisions for the Council, announces the final decisions.

Timekeeper : decides how long the presentations and the question/answer period will last, keeps track of time during the hearing, and stops teams that go overtime.

Administrator : develops rating sheet with other members, keeps notes, writes, and sends out any bulletins to the development teams.

Names: _____

Date: _____

Lunar Land Use

Lunar Council Information Sheet

Bulletins and Ratings

Your Council should issue bulletins periodically to give guidelines and announcements to all the development teams. An example is given below:

> Lunar Council Bulletin 1-1
>
> To: All development teams
> From: Lunar Council
> Regarding: Hearing timeline and financial background
>
> We have decided to allow each team 5 minutes to make their presentations following which the Council will have 10 minutes for questions and answers. Finally, the public will have another 10 minutes for questions and answers. Any variation to this policy will require permission from the Council before the hearing.
>
> Council members also will be asking you for your sources of money. We want to be sure that if your proposal is chosen, you will be able to build it.

You also will need to develop a rating sheet to judge each team fairly. An example is given below:

Group #	Feasibility 1-10	Pollution 1-10	Income 1-10	Planning 1-10	TOTAL
1					
2					

After all the teams have made their presentations, the Council retires and renders a decision on which team, if any, will be allowed to develop.

Names: _____

Date: _____

Lunar Land Use

Wrap-up Questions

1. Did your team work together well? Why or why not?

2. Do you think it is important to have hearings like this one before the Moon is developed? Why or why not?

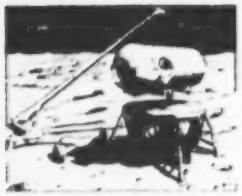
3. Do you think the Lunar Council's decision was fair? Why or why not?

4. Should we allow developments on the Moon? Why or why not?

5. Do you think the Moon should belong to everyone or to whomever can get there and use it first? Why?

6. How is the Moon and its development similar to the development of Antarctica?

7. What kind of environmental problems do you think we need to be aware of on the Moon?



Life Support Systems

Purpose

To design and build models of life support systems for a settlement on the Moon.

Background [also see "Teacher's Guide" Pages 14, 15]

A future lunar base will have to be a self-contained habitat with all the life support systems necessary for the survival of people, animals, and plants. In this series of activities, the students will be designing and building models of nine life support systems which are crucial to our successful settlement of the Moon.

The nine life support systems are:

"Air Supply,"
"Communications,"
"Electricity,"
"Food production and delivery,"
"Recreation,"
"Temperature control,"
"Transportation,"
"Waste management," and
"Water supply."

This activity is based on the Marsville activity on life support systems developed by the Challenger Center and is used with permission.

Preparation

Review and prepare materials listed on the student sheets. Separate student activity sheets are included for each of the nine life support systems. Spaces for answers are not provided on all sheets, so students will need extra paper.

In Class

After dividing students into teams, you may want to have each person assume a role on the team, e.g., organizer, recorder, researcher, builder, artist, writer, etc. Distribute a student activity sheet to each team.

Life Support Systems

Each team must define the requirements of their system, exploring how these requirements are currently being met on Earth. Team members will research the limitations and/or opportunities posed by the Moon's environment. The "Moon ABCs Fact Sheet" and maps of the Moon should be used as resource materials.

Each team will decide how the system will operate and what it will contain. A key part of the problem-solving process is the students' ability to evaluate the system solution in terms of whether it provides the greatest good and least harm to the persons and things affected.

Each model of a life support system must incorporate at least four facts from the "Moon ABCs Fact Sheet."

Models do not have to function physically, but each team member must be able to explain how the models should function.

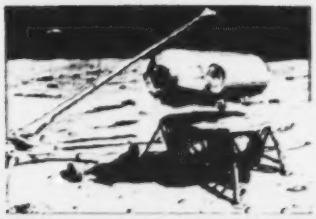
Wrap-up

Have each team share what they have learned with the entire class.

1. Did the students find that the Moon's environment placed limits on their designs of life support systems?

2. Did the students find opportunities for development on the Moon that could not happen on Earth?

3. Summarize the aspects and conditions of the Moon which make life support such a challenge.



Air Supply

Purpose

To design and build a model air supply system for a human settlement on the Moon.

Key Words

atmosphere

photosynthesis

Materials

"Moon ABCs Fact Sheet"

construction materials such as cardboard boxes and tubes, blocks, hoses, straws, string, pins, rubber bands, tape, etc.

Procedure

1. The atmosphere of Earth is a combination of several gases; review them from the "**Moon ABCs Fact Sheet**." What gas do humans and animals need to breathe in?

2. What primary gas do humans and animals breathe out?

3. What is photosynthesis?

4. During the process of photosynthesis, what gas must green plants take in ?

5. What gas do the green plants produce?

6. A process called electrolysis can separate water into hydrogen gas and oxygen gas. Another process is being developed which can extract oxygen from rocks and soil that contain it. Do you think these processes could be useful on the Moon? How?

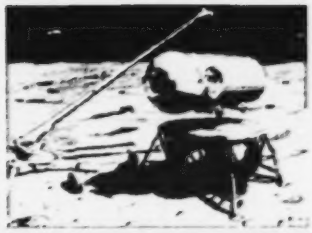
Air Supply

7. Review the "Moon ABCs Fact Sheet." Will the Moonbase settlers automatically be able to breathe the atmosphere or will special provisions need to be made?

8. Design an air supply system to be used by the Moonbase inhabitants which will rely on oxygen and carbon dioxide available only from the Moon's resources. You may assume that ample electricity will be available.

9. Construct a model of this system based on your design. It must include the application of at least four facts from the "Moon ABCs Fact Sheet." For example, how will the Moon's gravity affect the design of your system? Maybe your system will be very heavy but still portable by only a few Moonbase workers because the Moon's gravity is only 1/6th of Earth's gravity.

Sketch of my model



Communications

Purpose

To design and construct a model of a communications system to be used by people living and working on the Moon.

Key Words

communications

Materials

"Moon ABCs Fact Sheet"

construction materials such as cardboard boxes and tubes, blocks, hoses, straws, string, pins, rubber bands, tape, etc.

Procedure

1. What different ways do we have of communicating with each other here on Earth? Do some methods work better short distance than long distance? What are the strong points of each of these methods? What limitations does each have?

2. Why do you think communication would be important in each of the following situations:

   - Between Moonbase settlers within their constructed settlement,
   - Between settlers in the settlement and those conducting missions elsewhere on the surface of the Moon,
   - Between Moonbase and Earth (How long does it take for a radio signal to travel the distance between Earth and the Moon?)

3. Review the facts you have learned about the Moon. Do you think any of the communications methods on Earth (from Question 1) would be impractical on the Moon? Why or why not? Which communications methods on Earth do you think would be particularly useful on the Moon? What features of these methods might you have to modify?

4. Design a communications system to be used by the Moonbase inhabitants which will have components to satisfy the different situations listed in Question 2. You may assume that ample electricity will be available.

5. Construct a model of this system based on your design. It must include the application of at least four facts from the "**Moon ABCs Fact Sheet.**" For example, how will the Moon's gravity affect the design of your system? Maybe your system will be very heavy but still portable by only a few Moonbase workers because the Moon's gravity is only 1/6th of Earth's gravity.

Sketch of my model

Electricity

Purpose

To design and build a model electrical power supply system for a human settlement on the Moon.

Key Words

electricity

solar power

nuclear energy

Materials

"Moon ABCs Fact Sheet"

construction materials such as cardboard boxes and tubes, blocks, hoses, straws, string, pins, rubber bands, tape, etc.

Procedure

1. Think of all the things you do during a regular school day, from the minute you wake up until the time you go to sleep. List each activity which requires electricity.

2. What other activities in your town, city, or state use electricity?

3. What is the source of the electric power for your town or city? Is it a steam generating plant that burns natural gas, oil, or coal? Is it a nuclear-fission plant?

4. List other ways to produce electricity.

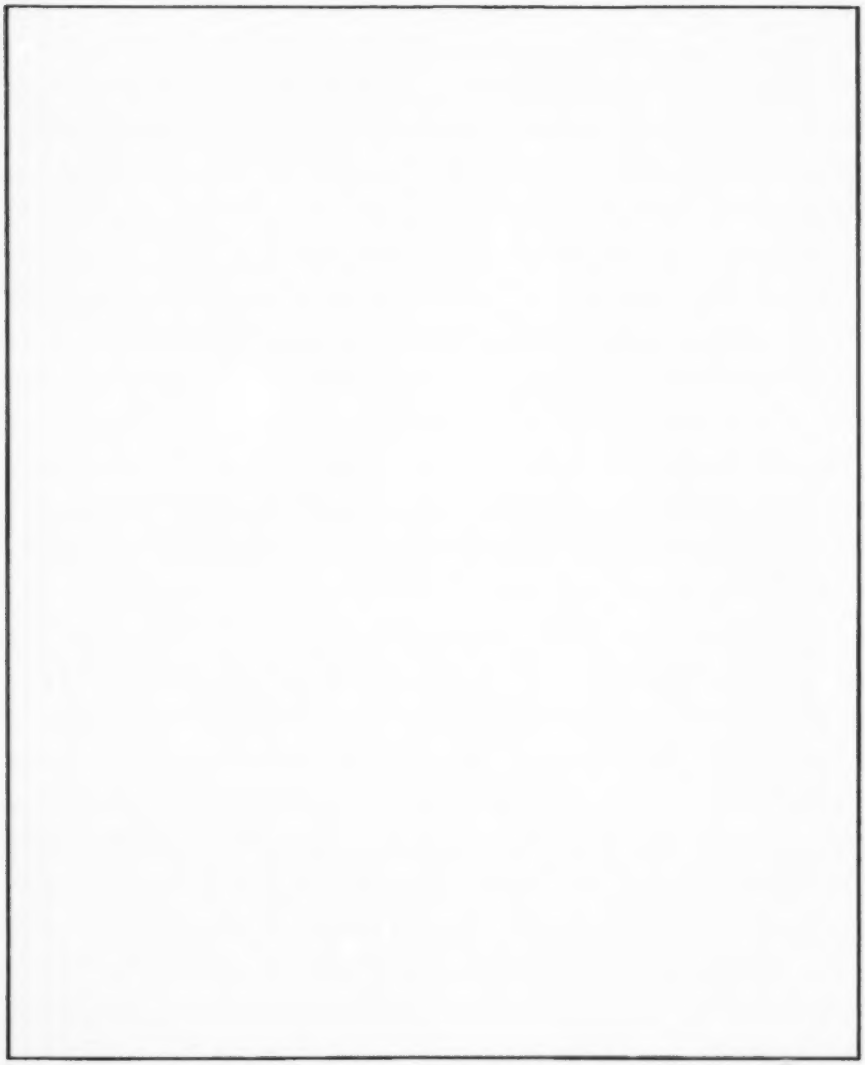
5. How is electricity transmitted from the generating plant to other places?

6. Review the facts you have learned about the Moon. Do you think the lack of atmosphere, natural gas, oil, and coal on the Moon would affect the production of electricity? How? Would materials have to be shipped from Earth? Should the lunar settlement rely on materials shipped from Earth? Your team's job is to supply the electricity needed by the life support systems at the Moonbase.

7. Review the "**Moon ABCs Fact Sheet.**" Design an electrical power generating plant and transmission system for the Moonbase inhabitants. Important issues to consider include pollution, radioactive waste storage, length of daylight on the Moon, and power storage.

8. Construct a model of this system based on your design. It must include the application of at least four facts from the "Moon ABCs Fact Sheet."

Sketch of my model



Food Production

Purpose

To design and build a model of a food production and delivery system for a human settlement on the Moon.

Key Words

food groups

nutrition

consumption

self-sustaining

Materials

food groups chart

"Moon ABCs Fact Sheet"

construction materials such as cardboard boxes and tubes, blocks, hoses, straws, string, pins, rubber bands, tape, etc.

Procedure

1. Review the basic food groups. What are examples of food in each group. What basic jobs for the body does each group perform? Make a chart on a separate paper with your answers.

2. With your class, make a list of the foods and liquids everyone consumed in the past 24 hours. Organize your list in the following way: Put each food group in a different column; then cross out all the items you consider "junk food" and cross out each item made from an animal which must eat another animal to live.

3. We know that, with the exception of carnivores, animals eat plants. But what do green plants "eat" in addition to carbon dioxide, sunlight, and water? Include in your answer a discussion of the nitrogen cycle.

4. It is likely that space in the Moonbase will be limited. Protein sources like cattle and vegetable sources like corn require substantial space for production. Reviewing your list from Question 2, what are other sources of protein which take less space? What fruits and vegetables could be produced in limited space?

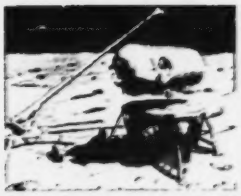
5. Review the "**Moon ABCs Fact Sheet**" to determine what conditions of sunlight exist. Remember that other teams are responsible for providing you with a water supply (which will probably have to be used cautiously or rationed,) with electricity, with a temperature control system in the constructed Moonbase, and with an air supply of carbon dioxide and oxygen for plants and animals you wish to grow. Remember also that all original stocks of plants and animals must be transported from Earth. With these reminders, your task is to design a food production and delivery system in the Moonbase which will:

   a) supply the inhabitants with all of their nutritional needs,

   b) be self-sustaining without additional stock from Earth, and

   c) provide products appealing enough that the inhabitants will enjoy eating their meals.

6. Construct a model of this system based on your design. It must include the application of at least four facts from the "Moon ABCs Fact Sheet." For example, how will the Moon's gravity affect the design of your system? Maybe your system will be very heavy but still portable by only a few Moonbase workers because the Moon's gravity is only 1/6th of Earth's gravity.



Recreation

Purpose

To design and build a model of recreational facilities for a human settlement on the Moon.

Key Words

entertainment

sedentary lifestyle

active lifestyle

Materials

"Moon ABCs Fact Sheet"

construction materials such as cardboard boxes and tubes, blocks, hoses, straws, string, pins, rubber bands, tape, etc.

Procedure

1. What value does entertainment have?

2. What do you do for entertainment? Brainstorm other forms of entertainment which people enjoy doing.

3. Reviewing your list from Question 2, what activities require you to consider the physical environment? What features of the environment does each activity depend upon?

Recreation

4. What value do you think entertainment would have on the Moon? (Would the Moonbase settlers need entertainment?)

5. Review the "**Moon ABCs Fact Sheet.**" Which of the recreational activities on your list do you think would be possible on the Moon? Include in your answer which activities would be the most practical and popular.

6. Remembering that the Moon has features different from those of Earth, what might be applied to developing new forms of recreation?

7. Design recreational facilities for the Moonbase inhabitants which satisfy any special recreational needs you think they will have and include some new forms of recreation based on the "Moon ABCs Fact Sheet." You may assume that ample electricity will be available.

8. Construct a model or models of the facilities based on your design. It must include the application of at least four facts from the "Moon ABCs Fact Sheet." For example, how will the Moon's gravity affect your designs?

Temperature Control

Purpose

To design and build a model temperature control system for a human settlement on the Moon.

Key Words

Farenheit

Celcius

Materials

"Moon ABCs Fact Sheet"

construction materials such as cardboard boxes and tubes, blocks, hoses, straws, string, pins, rubber bands, tape, etc.

Procedure

1. Review the clothes you and your classmates wear during each season of the year, both indoors and outdoors. You may want to write this information on a chalk board or paper.

2. How many degrees does the temperature have to change for you to switch from shorts to jeans, from bare hands to gloves, or to add a shirt over a swimming suit?

3. What effect do Sun, clouds, wind, and your own activity level have on the temperature choices you just made?

4. What are the coldest and hottest temperatures you ever experienced?

5. What is the number of degrees between these two extremes you felt?

6. Besides your selection of clothing, what other precautions did you take to protect your body?

7. Think back to a severe hot spell or cold snap your town experienced or that you heard about. List the effects of these temperature extremes on soil, plants, animals, buildings, water use, and electrical use.

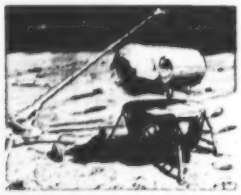
8. What different environments on Earth (both indoor and outdoor) could be uncomfortable or actually dangerous to us if we did not control the temperature to which our bodies were exposed?

9. What different ways do we have of controlling the temperature on Earth?

10. Review the "**Moon ABCs Fact Sheet.**" How do tempera tures on the Moon compare with temperatures on Earth? Will the Moonbase inhabitants be able to exist without special temperature controls on the surface of the Moon? How about in their constructed Moonbase settlement?

11. Design a temperature control system to protect the Moonbase inhabitants and their possessions/equipment both on the surface of the Moon and in their settlement. You may assume that ample electricity will be available.

12. Construct a model of this system based on your design. It must include the application of at least four facts from the "Moon ABCs Fact Sheet." For example, how will the Moon's gravity affect the design of your system? Maybe your system will be very heavy but still portable by only a few Moonbase workers because the Moon's gravity is only 1/6th of Earth's gravity.



Transportation

Purpose

To design and build a model transportation system for a human settlement on the Moon.

Key Words

transportation

Materials

"Moon ABCs Fact Sheet"

construction materials such as cardboard boxes and tubes, blocks, hoses, straws, string, pins, rubber bands, tape, etc.

Procedure

1. What are some different ways we transport people and goods on Earth?

2. What physical features of Earth do these methods require in order to function?

3. Write down the strong points and limitations of each transportation system you listed in Question 1.

4. What do you think would need to be transported on the Moon in each of the following situations:

   a) within the Moonbase settlement,

   b) between the settlement and other points on the Moon.

5. Review the "**Moon ABCs Fact Sheet.**" Do you think any of the transportation methods on Earth (from Question 1) would be impractical on the Moon? Why or why not?

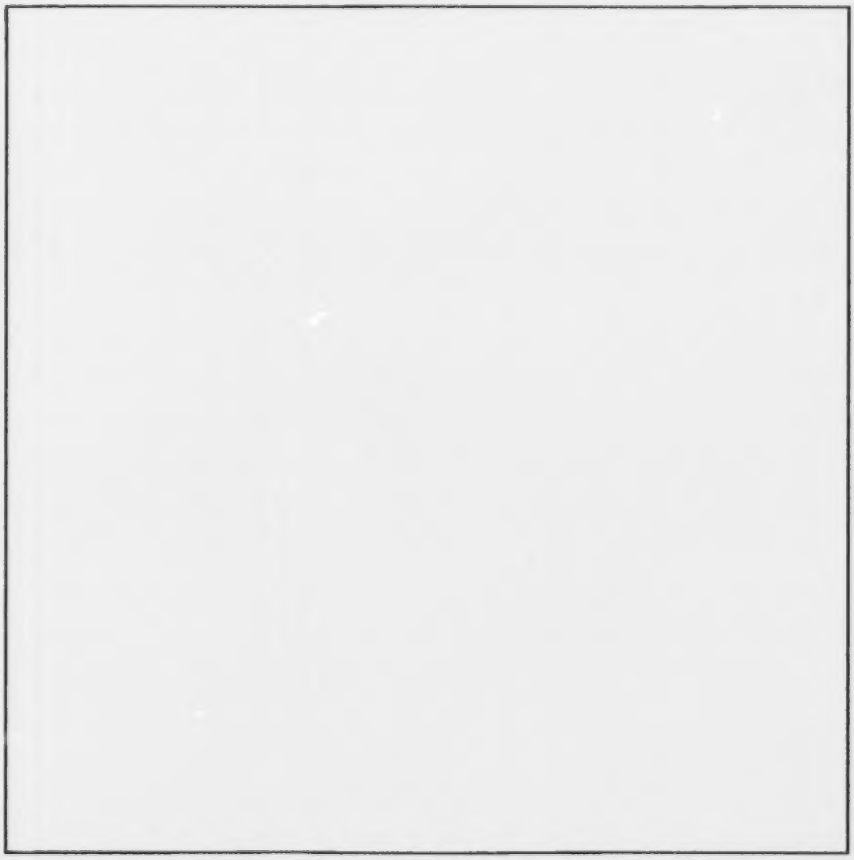
6. Which transportation methods on Earth do you think would be particularly useful on the Moon? What features might you have to modify?

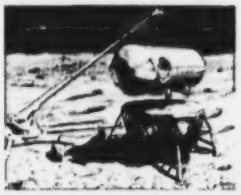
7. Design a transportation system to be used by the Moonbase inhabitants which will have components to satisfy the different situations they could encounter (Question 4). For this activity you may assume that some of the basic construction materials you need will be transported from Earth to the settlement. You may also assume that ample electricity will be available.

Transportation

8. Construct a model of this system based on your design. It must include the application of at least four facts from the "Moon ABCs Fact Sheet." For example, how will the Moon's gravity affect the design of your system? Maybe your system will be very heavy but still portable by only a few Moonbase workers because the Moon's gravity is only 1/6th of Earth's gravity.

Sketch of my model





Waste Management

Purpose

To design and build a model waste management system for a human settlement on the Moon.

Key Words

recycling

biodegradable materials

nondegradable

self-sustaining

Materials

"Moon ABCs Fact Sheet"

construction materials such as cardboard boxes and tubes, blocks, hoses, straws, string, pins, rubber bands, tape, etc.

Procedure

1. Your school, in many ways, is like a miniature town. It has a system for governance, health care, traffic control, a work schedule for its inhabitants, recreation, AND waste disposal. To get a better idea of how much waste your school generates every week, find out how many students plus teachers, administrators, other staff (and animals, if any) are regularly in the buildings.

2. Next, interview the cafeteria staff and the custodial staff for the answers to these questions:
   (a) What gets thrown away?
   (b) How many pounds get thrown away every week? Calculate how many pounds of trash this is for every person in the school.
   (c) Are there any items which can be recycled before disposal? If yes, what are the recycled items?
   (d) What items are biodegradable?
   (e) What is the garbage/trash packed in for removal?
   (f) Where is it taken?
   (g) According to building codes, how many toilets must there be to accommodate all the people?

3. Waste is a "hot" topic in our society. Why? Discuss what you know about the following phrases: Excessive packaging, landfills, toxic waste, disposable plastic goods, nondegradable material, water pollution, and air pollution.

4. In movies like those starring "Indiana Jones," well preserved, ancient artifacts are often found in the desert. Scientists also find preserved artifacts in polar ice; for example, mastodons or ancient people. Why aren't they decayed?

5. Review the "**Moon ABCs Fact Sheet.**" The Moonbase must be an enclosed, self-sustaining settlement. Just like your school, it must perform the basic functions of a town. Other teams are responsible for designing and constructing several other types of systems (air supply, communications, electricity, food production and delivery, recreation, temperature control, transportation, and water supply). Your team's job is to dispose of the waste which could be generated by these systems. Design a waste disposal system for the Moonbase. Be sure to decide what importance, if any, will be given to biodegradable materials, recycling, and the Moon outside of the constructed settlement.

6. Construct a model of this system based on your design. It must include the application of at least four facts from the "Moon ABCs Fact Sheet." For example, how will the Moon's gravity affect the design of your system? Maybe your system will be very heavy but still portable by only a few Moonbase workers because the Moon's gravity is only 1/6th Earth's gravity.

Water Supply

Purpose

To design and build a model water supply system for a human settlement on the Moon.

Key Words

water conservation

drought

Materials

"Moon ABCs Fact Sheet"

construction materials such as cardboard boxes and tubes, blocks, hoses, straws, string, pins, rubber bands, tape, etc.

Procedure

1 Think of all the things you do during a regular school day, from the minute you wake up until the time you go to sleep. List each activity which involves water.

2. Are there any water activities you could eliminate for a day? a week? longer?

3. What other activities in your town use water? Could any of those activities be eliminated?

4. During a dry summer, have you ever heard a public announcement that "water conservation measures are in effect"? What activities are affected by this announcement?

5. Imagine if summer drought continued for years, then how could water be conserved for people? for animals? for crops? for businesses?

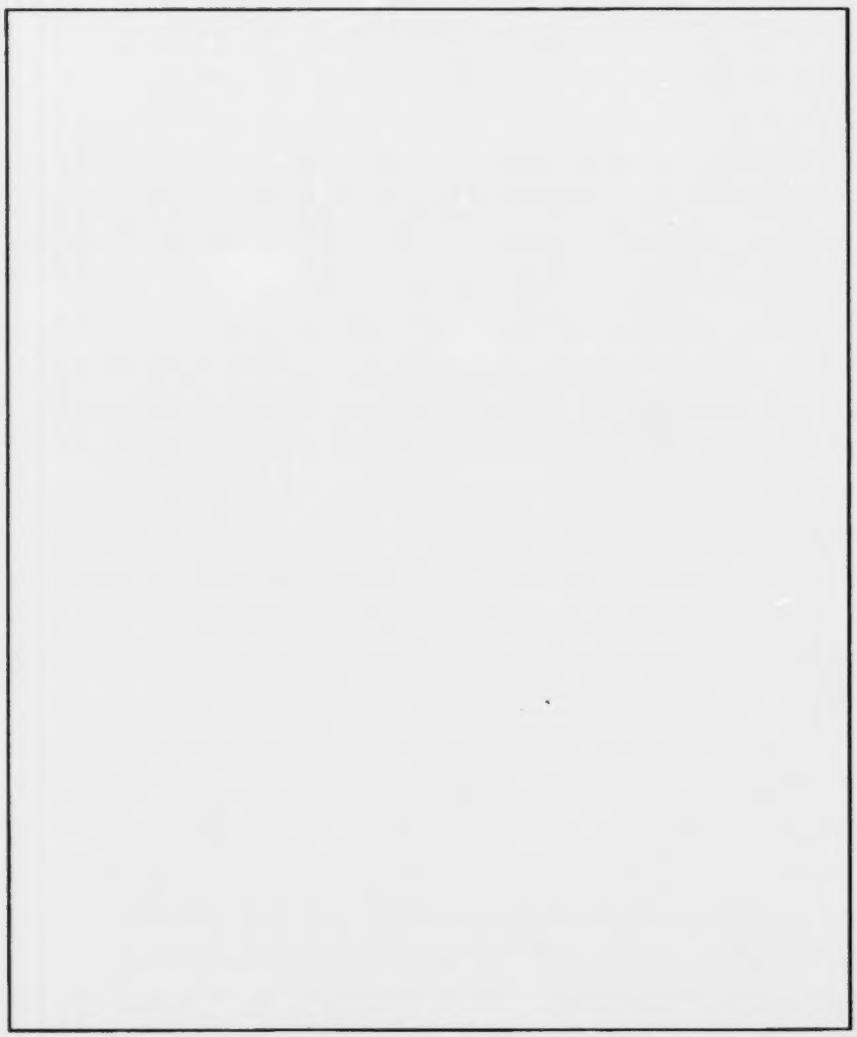
6. Review the "**Moon ABCs Fact Sheet.**" Where is the water on the Moon and in what form or forms does it exist?

7. Design a water supply system to be used by the Moonbase inhabitants which will rely only on water available from the Moon's resources. You may assume that ample electricity will be available.

Water Supply

8. Construct a model of this sytem based on your design. It must include the application of at least four facts from the "Moon ABCs Fact Sheet." For example, how will the Moon's gravity affect the design of your system? Maybe your system will be very heavy but still portable by only a few Moonbase workers because the Moon's gravity is only 1/6th of Earth's gravity.

Sketch of my model



Lunar Biosphere

Purpose

To build a biosphere that is a balanced, self-enclosed living system able to run efficiently over a long period of time.

Background [also see "Teacher's Guide" Pages 14, 15]

Earth is the ultimate **biosphere**, literally a "life ball." It holds and sustains all life known to humanity. As men and women look to traveling and living beyond our blue planet, we see conditions that are too harsh to sustain life as we know it.

Conditions on the Moon are not favorable for sustaining life because of the absence of water, organic topsoil, and **atmosphere**. Also **lunar** days (equal to 14 Earth days) and nights are very long. Water must be brought from Earth or made using oxygen from lunar **regolith** and hydrogen from Earth. Nutrients need to be added to lunar regolith and plants have to be grown in a self-enclosed system. What's more, artificial light must be used during the long, dark periods.

This activity challenges students to create a working model of a lunar biosphere that is a balanced, self-enclosed living system able to run efficiently over a long period of time.

Preparation

Review and prepare materials listed on the student sheet. Here are some suggestions.

Seedlings: About two weeks prior to this activity, sprout the seedlings for use in the biospheres. Successful biospheres have been made using mung, radish, and peanut. Tomato seedlings can also be used, as well as ferns, vines, and simple garden weeds.

Soil materials: Collect bins or bags to hold the variety of soil materials: vermiculite, permiculite, cinder, gravel, sand, silt, clay, and fertilizer.

Animals: Students should collect live critters to live in the biospheres. These can include -- insects (ants, cockroaches, beetles, etc.), mollusks (snails, slugs, etc.), arachnids (spiders, etc.), and crustaceans (sow bugs).

Plastic bottles for biospheres: Use 2-liter soda bottles with the black base. Remove the black base by submerging it in a large pot of hot (but not boiling) water. This softens the glue holding the base onto the bottle without melting the plastic. Take off the label. With an exacto knife or razor, cut off the top spout of the bottle. For safety, it is best not to allow students to do the cutting. You may place the spout with your other plastic recyclables as it will not be used in this activity. Prepare one container per student.

Lunar Biosphere

The students will plug the holes in the black base with wax, tape, or clay. The base must be watertight. They will then fill the base with a predetermined soil mixture. They will add water, seedlings, and animals as decided by the team. Finally, they will invert the plastic container into the base, seal it with clear, plastic tape, and label it. The label should include the student's name, names of team members, date, and time the biosphere was sealed.

In Class

After discussing the background information and purpose of this activity, divide the class into cooperative teams of 4 students each.

Biosphere mobiles

Have each team create a hanging mobile with the theme "Biosphere." Each hanging component represents one part of the living Earth system, e.g., water, plants, animals, people, air, Sun, soil, etc.

After mobiles have been balanced and hung from the ceiling, have the students predict what would happen if one part were removed or just shifted. Ask the students to shift or remove one part. Does the biosphere remain balanced? Ask the students to try to rebalance and hang their mobiles. Have them relate what they see to what might happen if a part of any biosphere is changed or removed.

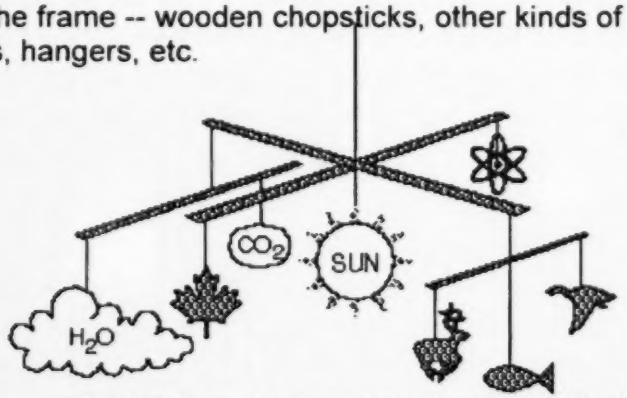
Materials

cardboard or heavy-weight paper

markers or crayons

string

something to use as the frame -- wooden chopsticks, other kinds of sticks, plastic drinking straws, hangers, etc.



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